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An Experimental Measurement of Metal Multilayer X-Ray Reflectivity Degradation Due to Intense X-Ray Flux

Mary Y. P. Hockaday

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ABSTRACT

AN EXPERIMENTAL MEASUREMENT OF METAL MULTILAYER X-RAY
REFLECTIVITY DEGRADATION DUE TO INTENSE X-RAY FLUX

BY

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The degradation of the x-ray reflection characteristics of metal multilayer Bragg diffractors due to intense x-ray flux was investigated. The Z-pinch plasma produced by PROTO II of Sandia National Laboratories, Albuquerque, New Mexico, was used as the source. The plasma generated total x-ray yields of as much as 40 kJ with up to 15 kJ in the neon hydrogen- and helium-like resonance lines in nominal 20-ns pulses.

Molybdenum-carbon, palladium-carbon, and tungsten-

carbon metal multilayers were placed at 15 and 150 cm from the plasma center. The multilayers were at nominal angles of 5° and 10° to diffract the neon resonance lines. The time-integrated x-ray reflection of the metal multilayers was monitored by x-ray film. A fluorescer-fiber optic-visible streak camera detector system was then used to monitor the time-resolved x-ray reflection characteristics of 135 Å-2d tungsten-carbon multilayers. A large specular component in the reflectivity prevented determination of the rocking curve of the multilayer.

Data for two separate shots were analyzed. For a pure neon gas shot at a power level of 420 TW, the reflectivity of the multilayer at 15 cm decayed rapidly with respect to the still-rising signal of the multilayer at 150 cm. The onset time of the decay corresponded to an integrated dose of 5.27 J/cm^2 .

For a neon implosion onto a vanadium-doped polyacrylic acid foam target shot, detailed modeling was attempted. The spectral flux was determined with data from 5 XRD channels and deconvolved using the code SHAZAM. The observed decay in reflectivity was assumed to correspond to the melting of the first tungsten layer. A "conduction factor" of 82 was required to manipulate the heat loading of the first tungsten layer such that the time of melting corresponded to the observed

decay. The power at destruction was 141 MW/cm^2 and the integrated energy at destruction was 2.0 J/cm^2 .

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INTRODUCTION

Metal multilayer x-ray diffractors, also known as layered synthetic microstructures (LSM's) and evaporated-sputtered multilayers (ESM's), are alternating layers (5-200 Å thick) of high and low atomic number materials deposited upon a substrate, as depicted in Figure 1. The resulting periodicity in the electron density gives rise to Bragg diffraction analogous to that in natural crystals.

The earliest efforts to create these artificial Bragg diffractors were those of Koeppel (Deubner, 1930) and Deubner (1930), who were unable to observe diffraction lines from the multilayer superlattice. Dumond and Youtz (1935; 1940) did observe diffraction from such a superlattice of copper and gold, but the layers interdiffused in a day or two at room temperature. Dinklage (1967) was successful in creating iron-magnesium multilayers with a shelf life of about a year.

In the 1970s multilayer construction was improved by, among others, Eberhard Spiller at IBM (Spiller et al., 1974 and 1976; Haelbich et al., 1978), who used evaporation techniques, and Troy Barbee at Stanford University (Barbee and Keith, 1978; Underwood et al., 1979), who used magnetron sputtering. Since then the field has grown rapidly in both applications and

Figure 1. Schematic of metal multilayer x-ray diffractor, showing alternating layers of high and low Z materials deposited upon a substrate. X rays are incident at angle θ and are Bragg-diffracted at angle θ .

availability of multilayers.

There are three main reasons for current interest in metal multilayers. First, the ability to vary the 2d-spacing gives the experimenter the capability to design a multilayer that can be optimized for a prescribed energy range. Second, since multilayers can be constructed with 2d-spacings between 25 Å and 200 Å, they complement the Langmuir-Blodgett molecular multilayers (70-130 Å) and natural crystals (less than ~ 35 Å) and extend the range for spectroscopic applications. The third reason is that the production process of evaporation or sputtering allows the deposition of multilayer coatings on curved substrates (Henry et al., 1982; Nagel et al., 1981), which permits construction of a variety of x-ray optical devices that are useful in plasma x-ray spectroscopy. In addition, multilayers do not have to be bi-layer periodic structures but can be graded in depth or laterally to meet bandpass needs (Lee, 1983; Nagel et al., 1981 and 1982). Even solid Fabry-Perot etalon systems can be fabricated (Barbee and Underwood, 1983; Bartlett et al., 1985). A recent conference on multilayer x-ray optics (Proc. SPIE Vol. 563, 1985) reviews the status of the field today.

For high-temperature plasma diagnostics, it is necessary to measure the x-ray characteristic line

radiations of highly stripped ions produced in the plasmas. Since metal multilayers are now available with the appropriate range of $2d$ -spacings, they are prime candidates for certain kinds of high temperature plasma diagnostics (Gilfrich et al., 1982; Day and Barbee, 1985). For very intense plasmas, the possibility arises that the radiation flux incident on the multilayer may change the multilayer x-ray reflection properties. The determination of flux levels at which the multilayer reflection properties change would permit compensation for the multilayer response, allowing for a more precise characterization of the plasma. In addition, normal incidence multilayer mirrors are being investigated for use in x-ray laser cavities (Ceglio et al., 1985) and their performance under fast intense flux conditions needs to be investigated.

A preliminary calculation for a Z-pinch plasma radiating 30 kJ of x rays indicates that the sudden temperature rise in a multilayer of interest at a useful distance would be on the order of a few electronvolts ($0.86\text{eV} = 10,000^\circ\text{K}$). Material properties in this temperature range produced by thermal pulses are not well understood. For this reason, it is necessary to perform experiments and model the results to get a better understanding of these material properties. This problem of

characterizing the changes in multilayer x-ray diffraction properties, both experimentally and through modeling, as the multilayer is subjected to intense bursts of x-ray radiation, is the subject of this dissertation.

The work is in two parts. Part I describes the room temperature characterization of metal multilayers, laying the foundation for understanding multilayers. It consists of two chapters and a summary. Chapter I-1 presents the physical and experimental x-ray characterization for the metal multilayer Bragg diffractors. Chapter I-2 discusses the different methods used to model such diffractors' room temperature x-ray reflection characteristics and describes the method chosen for analysis. It also presents the comparison of some experimental results with the chosen model. Part II describes the characterization of multilayers under intense flash-heat loading by x rays. It has six chapters. Chapter II-1 discusses the x-ray source criteria necessary to carry out the planned experiments as well as the specific characteristics of the source chosen. Chapter II-2 presents the time-integrated flash x-ray experiments and their results. Chapter II-3 discusses the time-resolved x-ray experiment, while Chapter II-4 discusses how the spectral intensity of the

x-ray radiation was determined. Chapter II-5 discusses the heating model used. In Chapter II-6 analysis of the time-resolved experimental data is discussed. A summary of Part II is then presented. Finally, a discussion of future work is given.

PART I

ROOM TEMPERATURE CHARACTERIZATION OF METAL MULTILAYERS

CHAPTER I-1

PHYSICAL AND X-RAY CHARACTERIZATION

Physical Characterization

Metal multilayers are alternating layers of materials of high and low atomic number, Z , deposited onto a substrate. Of particular interest is the simplest multilayer, which has a repeating structure of two layers, as depicted in Figure 2. Each high Z layer has the same thickness, d_H , as every other high Z layer, and every low Z layer has the same thickness, d_L . The combination of one high Z layer and one low Z layer is defined as a layer pair, which in this case is also one period of the multilayer. Each period has a thickness, d , equal to $d_H + d_L$. For convenience, the quantity, Γ , is defined as the ratio of the high Z -layer thickness to the period thickness.

The materials of a metal multilayer are alternatively deposited in a vacuum system onto a substrate, usually a piece of polished silicon crystal. The layer composition is determined by the manufacturing process. Ideally, a multilayer would have perfectly smooth interfaces and be deposited on a perfectly smooth and flat substrate. However, during production the depositing material may combine with other materials in

Figure 2. A bilayer periodic multilayer of alternating high and low Z materials of N layer-pairs or periods.

the vacuum system to form impure or transition layers. This type of structure can be detected through Auger depth profile analysis (Rachocki et al., 1984), x-ray diffraction analysis (Takagi et al., 1985), careful fitting of Bragg x-ray data taken at several wavelengths (Henke et al., 1985 and 1986), transmission electron microscopy, other techniques. Manufactured multilayers have layers and substrates that are not perfectly smooth and have roughness on the order of one or two atomic heights (Underwood and Barbee, 1981a and b). Such roughness degrades the x-ray reflection properties of the multilayers.

The physical thickness of the individual layers in the multilayer can be determined by in situ monitoring (Spiller et al., 1980) during the manufacturing process. Careful measurement of the x-ray reflection properties of the completed multilayer determines only average values for the physical thicknesses of the composite layers.

X-Ray Characterization

When a beam of x rays is incident upon a multilayer near the Bragg angle, it is diffracted. The intensity of the diffracted beam varies according to the angle of incidence and its energy or wavelength. The x-ray reflectivity of a multilayer is described by the curve of

the ratio of the diffracted intensity over the incident intensity as a function of angle when the incident energy is fixed, or as a function of energy when the incident angle is fixed.

For either description, the positions of the diffraction peaks are given by Bragg's law,

$$n\lambda = 2d\sin\theta, \quad (1)$$

where n is the order of the diffraction, λ is the incident wavelength, d is the d -spacing equal to the effective thickness of a period of the multilayer, and θ is the incident angle. In addition to the Bragg diffraction peaks there may be a specularly reflected beam. Measurement of the reflectivity curves can be done for both descriptions.

R vs. E Curve

To measure the x-ray reflection curve of a multilayer as a function of energy at a fixed angle, a continuously tunable wavelength source such as a synchrotron is necessary. The beam mechanics of a synchrotron light source are designed so that the x-ray beam is incident onto the multilayer at one fixed angle. The energy of the beam is stepped by use of a monochromator, and the diffracted intensity is measured at each energy setting point. The diffracted intensity is normalized by

dividing by the incident intensity.

A typical experimental R vs. E curve taken at the Stanford Synchrotron Radiation Laboratory is shown in Figure 3 (Bartlett et al., 1985). This particular curve is for a 10-layer pair, tungsten-carbon multilayer with a tungsten thickness of 20 Å and a carbon thickness of 31 Å at an incident angle of 60 degrees. The reflection properties of a multilayer are usually reported as the energy at which the peak was observed, the full width at half maximum (FWHM) of the reflection curve, the area under the reflection curve or R_E , and the peak reflectivity R .

R vs. θ Curve

To measure the x-ray reflection curve as a function of angle, a monochromatic, perfectly parallel x-ray beam is needed. A synchrotron source with a good monochromator produces an x-ray beam that is nearly monochromatic with very little beam divergence. Large beam divergence contributes to the apparent width of the reflection curve. For routine x-ray characterization of multilayers, use of synchrotron facilities is difficult to obtain and very expensive. In the kilo-electronvolt energy region, the width of a multilayer's diffraction pattern is very large (~5 mrad) compared with a natural

Figure 3. A typical reflectivity versus energy curve taken at Stanford Synchrotron Radiation Laboratory. LSM 82-152 was a 10-layer pair, tungsten-carbon multilayer with a tungsten thickness of 20 Å and a carbon thickness of 31 Å. The curve was taken at an incident angle of 60 degrees.

crystal, e.g., a potassium acid phthalate (KAP) crystal (~ 0.3 mrad). If the beam is first incident upon such a crystal at the proper angle, then the crystal not only helps to monochromatize the x-ray beam, but it limits its divergence, thereby contributing little to the measured width of the multilayer's diffraction pattern. This technique was used to measure the x-ray reflection curve as a function of angle. The experimental setup is schematically shown in Figure 4. A KAP crystal was held fixed and used to monochromatize and limit the beam divergence. The purified beam was then incident upon the multilayer, which was rotated through a succession of angles. The beam diffracted off the multilayer was measured by a gas flow proportional counter located at twice the angle of the multilayer.

A typical R vs. θ curve measured for a tungsten-carbon multilayer with a d -spacing of 70 Å and 120-layer pairs for an incident energy of 930 eV ($\text{Cu } L_{\alpha}$) is shown in Figure 5. The x-ray reflection properties are characterized by the peak angle, θ , and the peak reflectivity, P , the FWHM of the curve. The integral under the curve in radians is known as the integrated reflectivity, R_{θ} . This integrated reflectivity is related to the corresponding integrated reflectivity of the energy description, R_E , by

Figure 4. Experimental configuration for measuring reflectivity as a function of angle.

Figure 5. Measured reflectivity versus angle curve at Cu L_{α} wavelength for LSM 83-021, a tungsten-carbon multilayer of $2d \approx 70$ Å.

$$R_E = R_\theta \frac{dE}{d\theta} = R_\theta \left(\frac{nhc \cot(\theta) \csc(\theta)}{2d} \right),$$

where n is the order, h is Planck's constant, c is the speed of light, and θ is the Bragg angle.

All multilayers used in this investigation were measured at $\text{Cu } L_\alpha$ radiation with this technique. A summary of these measurements on the multilayers used in this investigation is given in Appendix A. The $\text{Cu } L_\alpha$ radiation was chosen because it was the most convenient radiation near the peak of the radiation that was to be observed during the impulse heating phase of this investigation.

In application, a source may not be monochromatic or give off a perfectly parallel beam of x-ray radiation. In this case, the multilayer diffraction is more complicated, and care must be taken in the interpretation of the intensity received at the detector.

CHAPTER I-2

CALCULATIONS OF MULTILAYER REFLECTION PROPERTIES

Calculations that determine the x-ray reflection and transmission of multilayer optics can be categorized into two approaches. The first is to extend the dynamical theory of diffraction of x rays from crystalline materials (Compton and Allison, 1935; Zachariasen, 1945) to metal multilayers (Underwood and Barbee, 1981a and b; Lee, 1981; Henke et al., 1985). The second approach is to solve the electromagnetic boundary-value problem for the steady-state electric and/or magnetic field amplitudes at successive interfaces or layers of the multilayer. This approach has been used extensively in optical thin-film theory (Born and Wolf, 1983; Weinstein, 1947) and can be used in the x-ray region with the inclusion of absorption (Parratt, 1954; Berning, 1963). These two approaches have been shown to be equivalent (Lee, 1981; Perkins and Knight, 1984) for non-crystalline multilayers.

Darwin-Prins and Modified Darwin-Prins

The Darwin-Prins method given here follows that presented by Compton and Allison (1935) and is based on the calculations of x-ray reflectivity for natural

crystals.

The basic formulism begins with x rays incident on an infinite set of planes or layers of a crystal, as depicted in Figure 6. The incident wave amplitude is denoted by T_0 and the reflected amplitude by S_0 . The reflected and transmitted amplitudes, S_r and T_r , at a plane, r , are related to the amplitudes S_{r-1} and T_{r-1} at the preceding plane, $r-1$, by the equations

$$T_r = (1-i\sigma)T_{r-1}\exp\left(\frac{-i2\pi d\sin\theta}{\lambda}\right) - iS_r\exp\left(\frac{-i4\pi d\sin\theta}{\lambda}\right), \quad (2)$$

and

$$S_r = -iS_r + (1-i\sigma)S_{r+1}\exp\left(\frac{-i2\pi d\sin\theta}{\lambda}\right), \quad (2b)$$

where s is the fractional amplitude that is reflected at a plane, σ is the fractional amplitude that is absorbed in the layer, d is the layer's thickness, θ is the incident angle, and λ is the incident wavelength of the radiation. The parameters s and σ are related to the atomic scattering factors f_1 and f_2 and the crystal structure factors F_1 and F_2 (Henke, 1981a and b) by the equations

$$\sigma = \frac{-r_0\lambda}{\sin\theta} n(f_1+if_2) \text{ and } s = \frac{-r_0\lambda}{\sin\theta} \phi(F_1+iF_2)P(2\theta),$$

where r_0 is the classical electron radius, $n(f_1+if_2)$ is the atomic scattering factor per unit volume, $\phi(F_1+iF_2)$ is the structure factor per unit volume, and $P(2\theta)$ is the polarization factor. The polarization factor is equal to

Figure 6. Schematic of a crystal containing an infinite number of crystal planes. T_i is the transmitted amplitude and S_i is the reflected amplitude at an interface.

unity for s polarization and equal to $\cos 2\theta$ for p polarization.

The ratio of the reflected amplitude to the incident amplitude is derived by solving Eqs. (2a) and (2b) for the case in which θ is near the Bragg angle, θ_B . This solution is given by

$$\frac{S_o}{T_o} = \frac{s}{(\sigma + \xi) \pm \sqrt{(\sigma + \xi)^2 - s^2}}, \quad (3)$$

where ξ is defined by the equation

$$\xi = \frac{2\pi d(\sin\theta - \sin\theta_B)}{\lambda}, \text{ and}$$

where θ_B is the Bragg angle. The reflectivity is calculated from the equation

$$R = \left| \frac{S_o}{T_o} \right|^2$$

for an infinite crystal or multilayer.

Henke et al. (1985) extend this result to the case of finite crystals or multilayers. The resulting equation for the Modified Darwin-Prins is

$$\frac{S_o}{T_o} = \frac{\frac{S_o}{T_o} (1 - x^{2N})}{1 - \left(\frac{S_o}{T_o} \right)^2 x^{2N}}, \quad (4)$$

where N is the number of planes and x is given by

$$x = (-1)^n \exp(-(\pm \sqrt{s^2 - (\sigma + \xi)^2})^2),$$

and n is the order of the diffraction. The $\pm$ sign of the

radical is chosen such that the real part of $\underline{x}$ is less than one to conserve energy.

For amorphous multilayers (Henke et al., 1985 and 1986), the unit cell is one period or repeating structure. For example, for a tungsten-carbon multilayer the unit cell can be depicted as one layer of tungsten and one layer of carbon, as shown in Figure 7. The structure factor sum or integral over the atoms in the unit cell is referenced to the displacement from some plane of symmetry. If the layers are crystalline in nature, this unit cell must be modified. The crystallinity will add extra diffraction effects in addition to those that are given by the superstructure of the multilayer.

This method is an efficient way of looking at purely periodic multilayers. In addition, density gradients representing roughness or transition layers can easily be incorporated into the unit cell as long as each period exhibits the same behavior throughout the multilayer. This method does not include the effect of a substrate, which is very small when the number of periods is large. In addition, the absorption in any particular layer is not apparent.

$$mF_1 = \int_{-d/2}^{+d/2} \left(n_C(z) f_{1C} + n_W(z) f_{1W} \right) \cos \left(\frac{4\pi z}{\lambda} \sin \theta \right) dz$$

$$mF_2 = \int_{-d/2}^{+d/2} \left(n_C(z) f_{2C} + n_W(z) f_{2W} \right) \cos \left(\frac{4\pi z}{\lambda} \sin \theta \right) dz$$

Figure 7. A unit cell and volume structure factors, $\underline{mF_1}$ and $\underline{mF_2}$, for a bilayer tungsten-carbon multilayer.

Optical Thin-Film Theory

Optical thin-film theory has been used for many years to calculate the optical properties of dielectric multilayers used as mirrors and interference filters in the visible portion of the spectrum. Figure 8 depicts a multilayer system and the labeling conventions that will be followed in this work. The multilayer consists of m layers, including the substrate. Medium $m+1$ is the exit medium. Medium 0 is the incident medium. Both the exit and incident media are assumed to be semi-infinite. The layer index, j , goes from 1 to $m+1$. Each layer j has a corresponding thickness, z_j , and complex index of refraction, n_j . The interfaces between the layers are assumed to be abrupt plane parallel and infinite in lateral extent. Each layer is assumed to be homogeneous and isotropic.

An electromagnetic wave with wave vector, $\vec{k}_0$, incident onto a multilayer with only two interfaces is depicted in Figure 9. The subscripts of the wave vectors and field vectors indicate the layer number, the superscript (t) indicates that the wave is progressing in the positive z direction (transmitted), and the superscript (r) indicates that the wave is moving in the negative z direction (reflected). The superscript $(+)$ indicates that the value of the fields should be taken on the side

Figure 8. Schematic of an m layer multilayer showing labeling conventions for the layers and interfaces.

Figure 9. Schematic depicting electric and magnetic field vectors at the first two interfaces of a multilayer system.

of the interface of increasing z , while the absence of a (+) indicates that the wave is to be taken on the side of the interface of decreasing z . All angles follow the x-ray convention of being measured from the surface instead of the optical convention of being measured from the normal.

The basis of the electromagnetic boundary-value problem approach is the electromagnetic continuity equations at an interface between two layers. Boundary conditions across an interface that are derived from Maxwell's equations require the normal components of the magnetic field, $\vec{H}$, to be continuous and require the tangential component of the electric field, $\vec{E}$, to be continuous across an interface. For the normal incidence case these conditions for the first interface of Figure 9 can be written as

$$E_o^{(t)} + E_o^{(r)} = E_1^{(t)+} + E_1^{(r)+} \quad \text{and} \quad (5a)$$

$$H_o^{(t)} - H_o^{(r)} = H_1^{(t)+} - H_1^{(r)+} . \quad (5b)$$

The magnetic field amplitude is related to the electric field amplitude by the magnitude of its corresponding wave vector and thus to the index of refraction of the corresponding medium. Equation (5b) can therefore be rewritten for nonmagnetic materials as

$$n_o E_o^{(t)} - n_o E_o^{(r)} = n_1 E_1^{(t)+} - n_1 E_1^{(r)+} . \quad (5c)$$

It is also known that the field amplitudes at both interfaces inside the first layer are related to each other by the phase factors $\exp(ik_1 z_1)$ and $\exp(-ik_1 z_1)$ since the wave travels through a distance of z_1 from one interface to the other. That is,

$$E_1^{(t)+} = E_1^{(t)} \exp(ik_1 z_1), \quad \text{and} \quad (6a)$$

$$E_1^{(r)+} = E_1^{(r)} \exp(-ik_1 z_1). \quad (6b)$$

The basic recursion relations between the electric field amplitudes on the $-z$ side of the first interface with that on the $-z$ side of the next interface are determined by combining the sets of Eqs. (5) and (6). This yields the relations

$$E_0^{(t)} = \frac{1}{2} \left(1 + \frac{n_1}{n_0} \right) E_1^{(t)} \exp(ik_1 z_1) + \frac{1}{2} \left(1 - \frac{n_1}{n_0} \right) E_1^{(r)} \exp(-ik_1 z_1), \quad (7a)$$

and

$$E_0^{(r)} = \frac{1}{2} \left(1 - \frac{n_1}{n_0} \right) E_1^{(t)} \exp(ik_1 z_1) + \frac{1}{2} \left(1 + \frac{n_1}{n_0} \right) E_1^{(r)} \exp(-ik_1 z_1). \quad (7b)$$

Equations (7a) and (7b) can be generalized for any succeeding two interfaces in a multilayer by replacing the 0 with $j-1$ and the 1 with j , giving

$$E_{j-1}^{(t)} = \frac{1}{2} \left(1 + \frac{n_j}{n_{j-1}} \right) E_j^{(t)} \exp(ik_j z_j) + \frac{1}{2} \left(1 - \frac{n_j}{n_{j-1}} \right) E_j^{(r)} \exp(-ik_j z_j) \quad \text{and} \quad (8a)$$

$$E_{j-1}^{(r)} = \frac{1}{2} \left(1 - \frac{n_j}{n_{j-1}} \right) E_j^{(t)} \exp(ik_j z_j) + \frac{1}{2} \left(1 + \frac{n_j}{n_{j-1}} \right) E_j^{(r)} \exp(-ik_j z_j) . \quad (8b)$$

The basic recursion relations (8a) and (8b) can be generalized to oblique angles of incidence by replacing n_j with η_j where

$$\eta_j = \frac{n_j}{\sin \theta_j} \quad (\underline{p} \text{ polarization}) \quad \text{and} \quad (9a)$$

$$\eta_j = n_j \sin \theta_j \quad (\underline{s} \text{ polarization}) . \quad (9b)$$

The electric field vector for $\underline{p}$ polarization is parallel to the plane of incidence and is perpendicular to the plane of incidence for $\underline{s}$ polarization. The angles, θ_j , are grazing angles that can be complex and are related to the incident angle θ_0 by the equation

$$\theta_j = \sin^{-1} \left(1 - \frac{n_0^2 \sin^2 \theta_0}{n_j^2} \right)^{1/2} . \quad (10)$$

For oblique angles of incidence, following Berning (1963) the quantity $k_j z_j$ becomes the effective phase thickness, ψ_j , of the layer; that is,

$$k_j z_j \rightarrow \psi_j = \frac{2\pi}{\lambda} \eta_j \sin \theta_j z_j . \quad (11)$$

Equations (8a) and (8b) then become for the general angle case

$$E_{j-1}^{(t)} = \frac{1}{2} \left(1 + \frac{\eta_j}{\eta_{j-1}} \right) E_j^{(t)} \exp(i\psi_j) + \frac{1}{2} \left(1 - \frac{\eta_j}{\eta_{j-1}} \right) E_j^{(r)} \exp(-i\psi_j) \quad (12a)$$

and

$$E_{j-1}^{(r)} = \frac{1}{2} \left(1 - \frac{\eta_j}{\eta_{j-1}} \right) E_j^{(t)} \exp(i\psi_j) + \frac{1}{2} \left(1 + \frac{\eta_j}{\eta_{j-1}} \right) E_j^{(r)} \exp(-i\psi_j) \quad (12b)$$

The reflectivity, R , and transmission, T , for a multi-layer are then given by

$$R = \left| \frac{E_o^{(r)}}{E_o^{(t)}} \right|^2 \quad \text{and} \quad T = \frac{\text{Real}[\hat{n}_{m+1}]}{n_o} \left| \frac{E_{m+1}^{(t)}}{E_o^{(t)}} \right|^2 \quad (13)$$

The recursion relations, Eqs. (12a) and (12b), are applied successively, starting from the substrate-exit medium interface with the initial condition that $\underline{E_m^{(r)}} = 0$ until the field amplitudes in the incident medium are calculated.

The matrix formulism arises from putting Eqs. (12a) and (12b) into matrix form.

$$\begin{bmatrix} E_{j-1}^{(t)} \\ E_{j-1}^{(r)} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \left(1 + \frac{\eta_j}{\eta_{j-1}} \right) \exp(i\psi_j) & \left(1 - \frac{\eta_j}{\eta_{j-1}} \right) \exp(-i\psi_j) \\ \left(1 - \frac{\eta_j}{\eta_{j-1}} \right) \exp(i\psi_j) & \left(1 + \frac{\eta_j}{\eta_{j-1}} \right) \exp(-i\psi_j) \end{bmatrix} \begin{bmatrix} E_j^{(t)} \\ E_j^{(r)} \end{bmatrix}$$

Factoring $\left(1 + \frac{\eta_j}{\eta_{j-1}} \right)$ out of the above equation gives

$$\begin{bmatrix} E_{j-1}^{(t)} \\ E_{j-1}^{(r)} \end{bmatrix} = \frac{1}{1-r_{j-1,j}} \begin{bmatrix} \exp(i\psi_j) & r_{j-1,j}\exp(-i\psi_j) \\ r_{j-1,j}\exp(i\psi_j) & \exp(-i\psi_j) \end{bmatrix} \begin{bmatrix} E_j^{(t)} \\ E_j^{(r)} \end{bmatrix}, \quad (14)$$

where $r_{j-1,j}$ is the Fresnel reflection coefficient for either p or s polarization, given by

$$r_{j-1,j} = \frac{\eta_{j-1} - \eta_j}{\eta_{j-1} + \eta_j}. \quad (15)$$

Equation (14) can be written in short notation as

$$\begin{bmatrix} E_{j-1}^{(t)} \\ E_{j-1}^{(r)} \end{bmatrix} = M_j \begin{bmatrix} E_j^{(t)} \\ E_j^{(r)} \end{bmatrix}. \quad (16)$$

Applying equation (16) $m+1$ times gives

$$\begin{bmatrix} E_o^{(t)} \\ E_o^{(r)} \end{bmatrix} = M \begin{bmatrix} E_{m+1}^{(t)} \\ E_{m+1}^{(r)} \end{bmatrix} = M_1 M_2 M_3 \cdots M_m M_{m+1} \begin{bmatrix} E_{m+1}^{(t)} \\ E_{m+1}^{(r)} \end{bmatrix}, \quad (17)$$

and the reflectivity and transmission are given by

$$R = \left| \frac{M_{21}}{M_{11}} \right|^2 \quad \text{and} \quad T = \frac{\text{Real}[n_{m+1}]}{n_o} \left| \frac{1}{M_{11}} \right|^2. \quad (18)$$

If the multilayer is periodic, then the matrix describing the period is the product of the matrices making up the period. Because of the nature of these matrices, the resultant matrix is unimodular. If P is the matrix that describes a period, and if there are N periods, then their resultant product (Born and Wolf, 1983) can be given as

$$P = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}, \text{ and} \\ P^N = \begin{bmatrix} P_{11}U_{N-1}(a) - U_{N-2}(a) & P_{12}U_{N-1}(a) \\ P_{21}U_{N-1}(a) & P_{22}U_{N-1}(a) - U_{N-2}(a) \end{bmatrix}, \quad (19)$$

where

$$a = \frac{1}{2}(P_{11} + P_{22}) \quad \text{and} \quad U_N(x) = \frac{\sin[(N+1)\cos^{-1}x]}{\sqrt{1-x^2}}.$$

The U_N are Chebyshev polynomials, and when the multilayer is periodic, their use saves computation.

The matrix formulism of Lee (1981) and others is equivalent to Eq. (16). The recursion relation used by Underwood and Barbee (1981a and b) can be similarly derived as Eqs. (12a) and (12b); however, they take the point at which to reference the recursion relation to be in the center of the layer instead of at the interface.

The advantages of the optical multilayer method are that the Chebyshev polynomial product allows quick computations of periodic systems, each layer in the multilayer can be unique, non-repeating roughness and transition layers can be incorporated, the effects of the substrate can be included, and the absorption within any particular layer can be readily calculated.

The main purpose of this thesis is to investigate the changes in the reflection properties of multilayers subjected to a harsh radiation environment. Under such conditions the multilayer is expected to absorb more radiation in its upper layers, producing physical changes in these layers. For this reason, it was necessary to use a method that would allow each layer to be unique,

and it was determined that the matrix method was the best method to use in this application. For room temperature evaluation of the multilayers, the Modified Darwin-Prins model was used in addition to the matrix method.

Data Base

For each of these methods, it is necessary to know the following multilayer properties:

- 1) layer composition
- 2) physical thickness of the layers
- 3) complex index of refraction or the atomic scattering factors.

If the physical thickness and material composition of the multilayer are known, then the appropriate optical constants must be determined. The atomic scattering factors are taken from the literature and are the key components of a data base necessary for any of the theoretical calculations.

The index of refraction is related to the atomic scattering factor of the composite material by the equation

$$n = 1 - \delta - i\beta,$$

where

$$\delta = \frac{r_0 \lambda^2}{2\pi} N f_1 \quad \text{and} \quad \beta = \frac{r_0 \lambda^2}{2\pi} N f_2.$$

Here $\overline{f_1}$ and $\overline{f_2}$ are the average atomic scattering factors, r_o is the classical electron radius, λ is the incident wavelength, and N is the number of molecules per unit volume. The data base is built on the tables of atomic scattering factors for elements of atomic number from 1 to 94 for energies of 100 eV to 2 keV (Henke et al., 1982) that have been recently extended to 10 keV (Auerbach and Tirsell, 1985). Since the time-resolved spectral information of the plasma source used in this investigation could be obtained down to 25 eV, it was necessary to extend the compilation down to 25 eV for the elements of interest: tungsten, carbon, aluminum, silicon, and molybdenum. The procedure used to extend the compilation for each element is described below.

Carbon. Carbon can exist in many forms, and its optical properties are extremely preparation-dependent. The research group at Deutsches Elektronen-Synchrotron (DESY) (Hagemann, Gudat, and Kunz, 1974) have compiled the real and imaginary parts of the dielectric constant for evaporated thin films of carbon with a reported density of 1.5 g/cm^3 . The $\overline{f_1}$ and $\overline{f_2}$ values are related to the dielectric constant by the equations

$$f_1 = \frac{\pi}{r_o} \frac{1}{N\lambda^2} \epsilon_1 \quad \text{and}$$

$$f_2 = \frac{\pi}{r_o} \frac{1}{N\lambda^2} \epsilon_2 \quad .$$

These values were used to determine the f_1 and f_2 values below 100 eV. For the f_2 data, it was necessary to scale the DESY data by 2.0/1.5 to be continuous with the Henke data at ~100 eV. This ratio is also the difference in the reported densities of the carbon films that the two investigators used. Likewise, for the f_2 values derived from the DESY data it was necessary to scale them by 1./1.04 to coincide with the Henke data.

Tungsten. Values for the real and imaginary parts of the index of refraction of tungsten taken from Lynch and Hunter (1985) were used to determine the atomic scattering factors between 25 eV and 47 eV using an assumed density of 19.3 g/cm³. Because their scattering data ended at 47 eV and Henke's compilation started at ~100 eV, a straight-line interpolation between the two data sets was taken for the f_1 values. For the f_2 values, Henke's compilation included points to 30.5 eV, and the calculated f_2 values from Lynch and Hunter (1985) were scaled to match Henke's data at that point.

Silicon. Silicon f_1 and f_2 scattering factors were needed to account for the silicon substrate. The real and imaginary parts of the complex index of refraction were taken from Edwards (1985). A density of 2.26 g/cm³ was assumed. Both the calculated f_1 and f_2 values were scaled by a factor of 0.97 to match the Henke data at

~100 eV.

Molybdenum. Molybdenum-carbon multilayers were also investigated; therefore, scattering factors for molybdenum were needed. The real and imaginary parts of the index of refraction were taken from Weaver, Krafka, Lynch, and Koch (1981) to calculate the f_1 and f_2 values, using an assumed density of 10.2 g/cm^3 for the range of 25-40 eV. The f_2 values were scaled by 0.974 to match the Henke compilation at 30.5 eV. The f_1 values were scaled such that the 40 eV point intercepted a line determined by the first three data points in the Henke compilation. The f_1 scaling factor was 2.8.

Aluminum. Aluminum f_2 scattering factors were needed to calculate the attenuation in the aluminum filters used. Both the f_1 and f_2 values were extended. The real and imaginary parts of the complex dielectric constant were taken from Hagemann et al. (1974), and the corresponding scattering factors were calculated using a density of 2.7 g/cm^3 . The resulting f_2 values were then scaled by 0.875 to match the Henke data point at 114 eV. The f_1 values were scaled by 0.958 to match the Henke data at ~ 100 eV.

Boundary Layer Roughness

As pointed out earlier in the introduction, the

layers in manufactured multilayers exhibit interfacial roughness, transition layers between two layers of different materials, and other imperfections. To calculate the actual x-ray response of a multilayer, these effects ought to be taken into account.

The effect of roughness on the scattering of visible and ultraviolet light from a surface has been extensively studied (Bennett and Bennett, 1969), and both scalar and vector theories have been developed (Beckmann and Spizzichino, 1963; Porteus, 1964). These theories have been applied to dielectric multilayers (Eastman, 1978; Carniglia, 1979; Elson, et al., 1983) and metal multilayers (Rosenbluth and Forsyth, 1981).

A straightforward way to incorporate roughness into the multilayer calculations is to use the matrix method (Carniglia, 1979). This allows each layer to have different characteristics if necessary and simplifies book-keeping.

A very simple way to account for the degradation of the reflection peak due to roughness is to use a Debye-Waller factor (Barbee, 1981). This method assumes that the roughness at the interfaces is random and exhibits a Gaussian distribution. The difference in the measured reflection peak and the calculated peak without roughness is related to the roughness of the interfaces by the

equation

$$\frac{P(\text{measured})}{P(\text{calculated})} = \exp\left[-\left(\frac{4\pi\Delta z \sin\theta}{\lambda}\right)^2\right] = \exp\left[-\left(2\pi n \frac{\Delta z}{d}\right)^2\right], \quad (20)$$

where Δz is the RMS roughness of the interface, θ is the incident angle, λ is the incident wavelength, n is the order of diffraction, and d is the d -spacing of the multilayer.

Optical profilometer measurements were taken on multilayer OVLA-130B-2 (tungsten-carbon). A series of seven measurements across the multilayer was averaged, and a 5.77-Å RMS roughness over a length of 700 μm was obtained. An example of the optical profilometer data for this multilayer is shown in Figure 10. Dr. B. L. Henke and his staff at Lawrence Berkeley Laboratory measured this multilayer at four diffraction orders for Al K_{α} radiation and two orders for Cu L_{α} radiation. These measured peak reflectivity values are given in Table 1. Also in Table 1 are the peak reflectivity values calculated by the matrix method using a $\Gamma=0.37$ and a $2d = 135$ Å for the tungsten-carbon multilayer. The last column of Table 1 gives the resulting Δz values derived from Eq. (20). The average value of the roughness for these x-ray measurements is $5.5 \text{ Å} \pm 1.0 \text{ Å}$, which is in very good agreement with what was observed by optical profilometry.

Figure 10. Example of the roughness data obtained with optical profilometry for multilayer OVLA-13CB-2. Information of the surface profile, the distribution of surface heights, and the autocovariance function assuming a Gaussian distribution of surface heights is obtained.

TABLE 1. MEASUREMENTS ON OVLA-130B-2

Energy	n	Measured P(%)	Calculated P(%)	Δz (Å)
1486.7	1	34.4	53.6	7.2
1486.7	2	6.5	15.7	5.1
1486.7	3	0.13	1.1	5.2
1486.7	4	0.10	5.3	5.4
929.7	1	29.0	39.2	5.9
929.7	2	4.8	8.5	4.0

SUMMARY PART I

In Chapter I-1 the x-ray and physical characteristics of metal multilayer x-ray diffractor elements were reviewed. Measurement techniques of the x-ray characteristics, both as a function of energy and as a function of angle, were presented. The set of measurements as a function of angle at Cu L_{α} wavelength for the multilayers investigated in this experiment can be found in Appendix A.

In Chapter I-2 the different methods for computing the x-ray properties were presented. Justification was given as to the choice of the thin-film matrix method for this investigation. The data base that allows calculation of the optical properties of the materials in the multilayers was discussed and a brief discussion of interfacial roughness presented. By taking into account the interfacial roughness with a Debye-Waller factor, the calculated values of the peak reflection were shown to match the experimental data.

PART II

MULTILAYER CHARACTERIZATION UNDER INTENSE FLASH

X-RAY LOADING

CHAPTER II-1

THE SOURCE AND ITS CAPABILITIES

To investigate the x-ray reflectivity changes of interest in metal multilayers under intense flash-heat loading, a heating source was required that would meet the following criteria:

- 1) is intense enough to melt at least the top few layers of the multilayer,
- 2) provides heating throughout the layers in which x-ray diffraction takes place,
- 3) has x-ray line components or could be used in conjunction with an x-ray source that provides x-ray line spectra that would permit measurement of the reflectivity of multilayers,
- 4) has a pulse duration of 10-50 nanoseconds,
- 5) has spectral characteristics that are known or measurable,
- 6) has a sufficient repetition rate to justify performing the experiment.

The time duration requirement and the intensity requirement eliminated the possibility of using conventional laboratory x-ray sources.

One promising source was a pulsed laser-produced plasma. For example, Kohler et al. (1978) used x rays

produced from a 10-J Nd glass laser with a 10-ns pulse incident on a copper target to heat a potassium acid pthalate (KAP) crystal 1 cm from the target. Potassium acid pthalate has a higher ratio of mass absorption coefficient to heat capacity compared with that of a tungsten-carbon multilayer; therefore, heating a tungsten-carbon multilayer would require even greater laser energy output. For this reason, the 10-J laser then available would not be adequate. Additionally, the x-ray spectrum from a laser-produced plasma is hard to quantify, making modeling difficult. It is of interest to note that during the course of this investigation, Kohler et al. (1985) increased the output of their Nd-glass laser to 100 J and measured the heating of metal multilayers with the same experimental configuration as for their KAP experiments in the time-integrated mode. Their results were described qualitatively, and no modeling was attempted.

Another method considered for heating the multilayer was to use resistive heating, obtained by running a current through the multilayer and using an auxiliary x-ray source to probe the multilayer's reflectivity. This type of experiment could be done in a standard laboratory setting; however, relating the changes in the multilayer structure and reflectivity due

to resistive heating to that due to x-ray heating was judged unnecessarily complicated. In addition, modeling would have been almost impossible since investigators have even had difficulty modeling the change of state of resistively heated planar single material foils (Logan et al., 1977).

Another possible x-ray source that could be used to do the heating as well as provide radiation components for probing multilayer reflection properties was a fast Z-pinch. A Z-pinch is a machine that sends large amounts of current along its z -axis. The current induces a strong magnetic field around the z -axis, and the resulting $I d\vec{l} \times \vec{B}$ force collapses the plasma along that axis. Fast Z-pinch produce high-intensity x rays efficiently (Hammel and Jones, 1984; Spielman et al., 1985).

A particular Z-pinch machine that appeared useful was the recently upgraded accelerator, PROTO II, at Sandia National Laboratories in Albuquerque, New Mexico. Of particular interest was its gas puff mode in which a cylindrical annulus of ionized low-density noble gas is imploded. By changing the noble gas, different lines in the kiloelectronvolt energy region of the x-ray spectrum can be produced (Maxon and Wainwright, 1984; Spielman et al., 1985). These lines in the kiloelectronvolt region

of the spectrum can contain as much as 10 percent of the total radiation yield. Specifically, radiation from neon gas puffs looked very promising. A typical neon gas puff implosion on PROTO II produced 30 kJ of total radiation, of which 2-3 kJ were in the kiloelectronvolt spectral region. Of particular importance was the fact that the 2-3 kJ of kiloelectronvolt radiation was mostly confined to the hydrogen- and helium-like resonance lines at 1022 and 922 eV, as shown in Figure 11. Because of the low level of background and continuum in this region of the spectrum, these lines appeared suitable for probing the multilayer x-ray reflectivity characteristics.

There were two additional features of PROTO II that made it attractive. One was that it averages a shot a day and that a run of several months' duration had already been scheduled that would permit adequate experimentation. The second feature was that PROTO II already had an experimental team that was diagnosing the plasma characteristics. Since diagnostic ports were available on this machine and administrative arrangements were feasible for this collaboration, it was decided to field the experiment on PROTO II.

PROTO II

PROTO II (Johnson, 1976; Martin et al, 1976a and

Figure 11. Time-integrated spectrum taken by M. A. Palmer of Sandia Laboratories with a potassium acid phthalate curved-crystal spectrograph.

1976b) is a multimodule water-insulated, pulsed power machine. A drawing of PROTO II is shown in Figure 12. Eight 100 kV oil-insulated Marx generators feed sixteen 7.5-nfd water-filled capacitors. The stored energy is switched through eight SF_6 gas trigatron switches from the water capacitors to sixteen water-insulated lines. In each set of lines the first pulse-forming line stores the energy from the capacitor, then a self-breakdown switch closes and charges the pulse-forming line in about 60 ns. The electrical energy is fed into the modified vacuum diode as shown in Figure 13. The hollow cylindrical gas annulus is injected into a 2.0-cm-long gap between the gas nozzle in the center of the cathode and a Ni wire mesh strung on stainless steel return current posts that are part of the anode. The energy flows into the diode in a fast 4×10^6 -ampere pulse with a FWHM of 55-60 ns. The gas implosion time, defined as the time between the arrival of the current pulse and the peak of the radiation pulse, is typically between 60-80 ns, depending on the nature and mass of the gas used.

The converging pulse lines were approximately level with 8 radial diagnostic ports that exited at 75 degrees from the z -axis. These pulse lines were water-insulated, which means they were under some three feet of water. Any diagnostic that was used on these ports had to be

Figure 12. An artist's conception of the PROTO II Z-pinch, pulse-power machine. Drawing is courtesy of Rick Spielman, Sandia National Laboratories.

PROTO II

Figure 13. Schematic of the gas nozzle/target assembly showing the configurations of the target, nozzle, return current posts, and electrical feed. Drawing courtesy of Sandia National Laboratories.

vacuum-compatible on the inside and water-compatible on the outside and could not rust or pollute the very clean water. Near axial ports on the machine were not immersed. Additional precautions had to be taken when designing the experiment. For example, apparatuses that were attached to the machine had to be more than a certain minimum distance from the current-carrying lines to ensure against electrical arcing.

Sandia Diagnostics

The experimental team of PROTO II fields a variety of time-integrated and time-resolved diagnostics for each shot. Data from these are used to characterize the plasma source. Time-integrated diagnostics include 2 or 3 x-ray pinhole cameras, a curved-crystal KAP spectrograph, and a grazing incidence x-ray spectrograph. The major time-resolved diagnostics of interest that are fielded are 6 x-ray diodes (XRD's) and 2 thin-film bolometers.

Time-Integrated Diagnostics

X-ray pinhole cameras. Quantitative information on the size of the plasma and the location from which energy was emitted inside the plasma was obtained from x-ray photographs taken with pinhole cameras. The x-ray pinhole cameras were fielded by M. A. Palmer and A. Widman.

Photographs with different energy sensitivities are obtained in two ways. One way that spectral differentiation can be obtained is by using a film pack with several different films in a stack. The first film's energy response is its inherent x-ray response (Henke et al., 1984a and b), convolved with the response of the prefilter. The first piece of film acts as a filter for the second piece of film; therefore, the second film's energy response is the convolution of the transmission of the prefilter and the first piece of film and the x-ray response of the second piece of film. Succeeding film responses are calculated in a similar manner.

The film packs used on PROTO II contained two pieces of film. The films were RAR 2497 and SB-5, in that order. The energy response of the stack of films convolved with a 12.7- μ m beryllium prefilter transmittance is shown in Figure 14. The first piece of film gives an indication of where x rays ≥ 1 keV are being emitted from the plasma, while the second piece of film indicates the source distribution of x rays of ≥ 2.2 keV. A sample photograph of an image taken on the first piece of film is shown in Figure 15.

The second way spectral differentiation is obtained is by using the critical angle characteristics of x-ray mirrors to cut out the high-energy portion of the spec-

Figure 14. Spectral response of the two-layer film pack for the x-ray pinhole cameras fielded by M. A. Palmer.

Figure 15. Example of a kiloelectronvolt pinhole image of the PROTO II source.

trum. This low-energy spectral imaging is obtained by using two carbon mirrors at 3.72° grazing incidence after the pinhole to keep photons with energies higher than 284 eV from being incident on the x-ray film. A 2000-Å gold filter is used as a prefilter, and the x-ray film is RAR 2497. The sensitivity as a function of energy for the carbon mirror channel is shown in Figure 16. This pinhole camera records an image of the plasma in the 100-284 eV spectral range.

In summary, images from the pinhole photographs gave information about the source in the spectral ranges from 100-284 eV, ≥ 1 keV, and ≥ 2.2 keV.

Potassium acid phthalate curved-crystal spectrograph. The KAP spectrograph consists of a convex-curved KAP crystal of radius of curvature 2.5 cm and a non-concentric curved-film plane of radius of curvature 8.3 cm. The spectrograph is usually fielded with a 12.7- μ m beryllium entrance window and RAR 2497 film. In this configuration, it gives time-integrated spectral information in the range from 0.8 keV to ≤ 3 keV. An example of the type of spectral information obtained with this instrument is shown in Figure 11. For the present experiments this instrument was fielded by the team of M. A. Palmer, A. Widman, and B. A. Hammel.

Grazing incidence spectrograph. The grazing

Figure 16. Absolute spectral sensitivity of the carbon mirror pinhole camera. Transmission of the 2000-Å gold filter has been taken into account.

incidence spectrograph gives qualitative spectral information in the range 20 Å to 200 Å, using a 1200-grooves/mm gold-coated grating at 88° angle of incidence from the normal with a 10-μm entrance slit. The detection film used is Kodak 101-06. The reason that these data are qualitative is that spectral sensitivity of films at grazing incidence is uncertain. Again, this instrument was fielded by the team of M. A. Palmer, A. Widman, and B. A. Hammel.

Time-Resolved Diagnostics

X-ray diodes. Temporal spectral information in specific energy bands is obtained with XRD's. An XRD consists of a filter, a grid, and a photocathode. A positive voltage is applied between the grid and the photocathode. The grid collects the electrons produced by the photoelectric effect when x rays are incident upon the photocathode. The loss of electrons from the photocathode is registered as a current pulse. The time resolution of the detector is determined by the spacing between the grid and the photocathode. The transmission of the filter in conjunction with the photocathode's quantum efficiency determines the spectral window of the XRD.

Six XRD's were fielded by R. B. Spielman and S. F.

Lopez for this experiment. Three of the XRD's were sensitive to x rays with energies below 1 keV, and three were sensitive to x rays at 1 keV and above.

The x-ray flux the plasma produces is of such intensity that in order to keep the XRD's that are sensitive to low-energy x rays from saturating, the XRD's have to be either meters away or the flux must be cut down in some way that still preserves the low-energy component. Therefore, the three low-energy XRD's in these experiments were pinhole imaged. In other words, the source was viewed by the XRD's through a pinhole such that the image of the source was entirely within the detectors' effective area. The three low-energy XRD's had aluminum photocathodes and were all 162.56 cm from the source. The photocathode quantum efficiency was taken from Day et al. (1981a and b). The Channel 1 XRD had a filter of 250 nm of parylene and observed the source through a 150- μ m-diameter pinhole located halfway between the source and the detector at a distance of 82.55 cm. The Channel 2 XRD had a filter of 0.75- μ m aluminum and viewed the source through a 500- μ m-diameter pinhole also located halfway between the source and the detector at a distance of 82.55 cm. The Channel 3 XRD had a filter of 2- μ m Kimfol and viewed the source through a pinhole of 500- μ m-diameter. The x-ray responses of Channels 1-3 are given

in Figure 17 and include the effective solid angle of the detectors.

The three high-energy XRD's used gold photocathodes, were located at 162.56 cm from the source, and had effective areas of 0.75 square centimeters. The Channel 4 XRD had a filter of 2- μ m zinc. The Channel 5 XRD had a filter of 0.5-mil saran and 2-mil Kapton, and the Channel 7 XRD, following the labeling convention of Spielman, had filters of 0.5- μ m aluminum and 2- μ m Kimfol. The x-ray responses of Channels 4-7 are shown in Figure 18 and include all geometrical factors.

Data obtained from these six XRD's can be used to determine the spectrum produced by the source as a function of time.

Thin-film bolometers. Time-resolved thin-film bolometers (Mix et al., 1981) were fielded in these experiments by D. L. Hanson to measure x-ray fluence. Total energy yields were measured with a bare-nickel bolometer, and the yield of the radiation in the 500-eV to 40-keV range was measured with a beryllium-parylene-filtered gold bolometer. Response functions of the bolometers fielded are shown in Figure 19. The data from the bolometers gave energy yields for each shot.

Figure 17. Spectral sensitivity of XRD Channels 1-3, assuming 1-cm^2 source and taking into account all geometrical factors.

Figure 18. Spectral sensitivity of XRD Channels 4, 5, and 7, assuming a 1-cm² source and taking into account all geometrical factors.

Figure 19. Spectral energy response of the two thin-film bolometers fielded by D. L. Hanson.

Rough Calculation of Heating Capabilities of PROTO II

To determine whether the surface of a multilayer will melt, the specific energy absorbed during a typical neon gas puff implosion can be calculated and compared with the enthalpy needed for heating and melting the multilayer material. In a tungsten-carbon multilayer, the tungsten has a higher absorption coefficient than carbon and therefore will reach a higher temperature. The enthalpy needed to heat the tungsten through melting,

ΔH_W , is given by the equation

$$\begin{aligned}\Delta H_W &= H_W(T_{\text{melting}}) - H_W(298^\circ\text{K}) \\ &= 552.2 \text{ J/g}.\end{aligned}\quad (21)$$

The specific energy absorbed, ξ , is given by the equation

$$\xi = \int_0^t \int_0^\infty \frac{d^2S}{dEdt} T_f(E) \mu_W(E) (1 - R(E)) dEdt, \quad (22)$$

where $\frac{d^2S}{dEdt}$ is the incident spectral flux in $\text{W/cm}^2\text{-keV}$,

T_f is the transmission function of any prefilter, μ_W is the mass absorption of tungsten in cm^2/g , and R is the reflection coefficient for the multilayer stack. To determine whether PROTO II would be adequate, some understanding of the nature of the incident spectrum was needed.

If 29 kJ is a typical number for the total radiated energy and there are 2 kJ of x-ray line radiation in a

20-ns pulse, the spectrum can be approximated as consisting of a blackbody continuum and two lines at 1022 eV and 922 eV with 1 kJ total energy in each. The blackbody temperature can be calculated by taking the energy attributed to the continuum, E_c , and using the Stefan-Boltzmann equation; thus,

$$B = \sigma T^4 \frac{\text{MW}}{\text{cm}^2}, \text{ and}$$

$$\sigma T^4 = \frac{E_c}{A_s \Delta t}, \quad (23)$$

where B is the brightness, $\sigma = 5.67032 \times 10^{-8} \text{ W/m}^2 \text{ } ^\circ\text{K}^4$, A_s is the source surface area, and Δt is the x-ray pulse width. The source is taken to be a cylinder 2.0 cm long with a 2-mm diameter, giving a surface area of 1.3194 cm^2 . To calculate E_c , the energy in the lines is subtracted from the total energy, giving 27 kJ. Solving Eq. (23) for the average blackbody temperature, T , gives

$$T = \left(\frac{E_c}{A_s \Delta t \sigma} \right)^{1/4}; \text{ therefore,}$$

$$T = \left(\frac{27 \text{ kJ} \times 1000 \text{ J/kJ}}{1.3194 \times 10^{-4} \text{ m}^2 \times 20 \times 10^{-9} \text{ s} \times 5.6703 \times 10^{-8} \text{ W/m}^2 \text{ } ^\circ\text{K}^4} \right)^{1/4}$$

$$= 6.517 \times 10^5 \text{ } ^\circ\text{K} = 56.6 \text{ eV.}$$

Using this temperature in Planck's law,

$$B_E = \frac{d^2 S}{dE dt} = \frac{(2c)}{(hc)^3} \left(\frac{E^3}{e^{(E/kT)} - 1} \right) \frac{\text{MW}}{\text{cm}^2 \text{-sr-keV}}, \quad (24)$$

gives the average spectral distribution.

The complete spectral distribution is this black-body spectrum plus the two lines in the kiloelectronvolt region. From the spectrum shown in Figure 11 the half width at half maximum (HWHM) of the H-like resonance line was determined to be 10.1 eV, and the HWHM of the He-like resonance line was determined to be 8.3 eV. The line profile shape can be assumed for convenience to be Lorentzian, following the equation

$$I_{\text{line}}(E) = \frac{1}{\pi \text{HWHM}} \frac{C_{\text{line}}}{\left[\frac{E - E_{\text{line}}}{\text{HWHM}} \right]^2 + 1} \quad (25)$$

This equation, when integrated over energy, gives the coefficient C_{line} to describe a line of 1-kJ total energy. The appropriate coefficient is needed.

$$C_{\text{line}} = \frac{E_{\text{line}}}{4\pi k t A_s} \quad (26)$$

The coefficient C_{line} for a 1-kJ, 20-ns pulse is therefore

$$C_{\text{line}} = 3.02 \times 10^9 \frac{\text{J}}{\text{sr-s-cm}^2}$$

Combining the corresponding distributions for the two lines and the blackbody continuum gives a representation of the incident spectrum shown in Figure 20.

For a tungsten-carbon multilayer of $2d=100 \text{ \AA}$, $\Gamma =$

Figure 20. Estimated spectra' shape for the x rays produced by PROTO II.

0.4, at an incident angle of 8.08 degrees, and with tungsten as the top layer, the calculated incident spectrum would heat the multilayer at 15 cm such that the first seven layers of tungsten would melt. A tungsten-carbon multilayer of $2d = 141 \text{ \AA}$ and $\Gamma = 0.43$ at 5 degrees incidence would get hot enough to melt the first 5 layers of tungsten. This calculation disregards the effects of conduction.

Because of the scale of the layers in the multilayer, thermal conductivity is very important and should be included in all detailed modeling that is done. This is illustrated by the following oversimplified discussion.

The sound speed of tungsten (Handbook of Chemistry and Physics, 1980) is such that a longitudinal wave could make 890 round trips across a $30\text{-}\text{\AA}$ layer in one nano-second. Therefore, the layer could reach equilibrium in the 20-ns x-ray pulse. Since the tungsten layers absorb more radiation and heat up faster than the carbon layers, the cooler carbon layers will conduct heat away from the tungsten layers. The assumption is made that there is a 1°K -temperature difference between two $30\text{-}\text{\AA}$ tungsten layers separated by a $40\text{-}\text{\AA}$ carbon layer. Then, using a nominal thermal conductivity of $0.05 \text{ W/cm-}^\circ\text{K}$ (Touloukian et al., 1970a) for the carbon layer, the amount of heat

taken away is

$$q = 0.05 \frac{\text{W}}{\text{cm}^{\circ}\text{K}} \times \frac{1^{\circ}\text{K}}{40 \times 10^{-8} \text{cm}}$$

$$= 1.25 \times 10^5 \frac{\text{W}}{\text{cm}^2} = 5.22 \times 10^5 \frac{\text{cal}}{\text{cm}^2\text{-s}} .$$

Dividing this number by the areal density of the carbon layer and multiplying by the x-ray pulse duration of 20 ns gives the total amount of heat taken away during the pulse Q.

$$Q = \frac{5.22 \times 10 \times 20 \times 10^{-9}}{8.0 \times 10^{-7}} = 1.3 \times 10^4 \text{ cal/g.}$$

The amount of energy that was absorbed in the first tungsten layer was calculated from the above method to be only $\sim 6 \times 10^4$ cal/g. Therefore, a temperature difference of only 4.6°K would allow all the heat of the tungsten layer to be carried away. This means that conduction will definitely play a crucial role in the calculations.

CHAPTER II-2

TIME-INTEGRATED EXPERIMENTS

The purpose of this phase of the investigation was to determine whether the overall experimental concept was sound. In addition, it allowed the author to become familiar with PROTO II and its physical constraints before designing the second phase of the investigation, the time-resolved experiments.

Two metal multilayer spectrometers were used in the experiments. Each spectrometer had provisions for a prefilter, a metal multilayer as the diffraction element, a postfilter, and a film pack as the detector. Spectrometer 1 was designed to have the metal multilayer diffraction element located 212 cm from the x-ray source. At this distance it would diffract the incident radiation without suffering physical damage due to radiation. Spectrometer 1 provided the "control" spectrum. Spectrometer 2 was designed such that the metal multilayer diffraction element was only 15 cm from the plasma center where it could be expected to experience physical changes during the radiation pulse. These physical changes could be detected by comparing the difference in reflected spectra from the two spectrometers. Initial port assign-

ments for this experiment placed Spectrometer 1 at a 13.5 degree port and Spectrometer 2 at 75 degrees from the z-axis. Both ports viewed the plasma from the same side. A general schematic of the two spectrometers is shown in Figure 21.

Spectrometer 1

A "safe" distance for the metal multilayer of Spectrometer 1 was determined to be 212 cm from "back of the envelope" calculations similar to those described in Chapter II-1. At this distance the multilayer would receive approximately 1/200 the flux the metal multilayer at 15 cm from the source would receive. Originally, a port at 13.5 degrees from the z-axis was assigned for the use of Spectrometer 1. A distance of 212 cm would require a stainless steel pipe about 30 inches long. The distance from the detection plane to the metal multilayer was made as short as possible to minimize the possibility of mechanical interference with other experiments. A photograph of the components of Spectrometer 1 is shown in Figure 22. The manual valve was used as a shutter-light shield to protect the x-ray film during transit to and from PROTO II.

Spectrometer 2

The separations of the individual spectrometer

Figure 21. General schematic of the two spectrometers used at PROTO II.

Figure 22. Photograph of the components of Spectrometer 1 used in the time-integrated experiments.

components of Spectrometer 2 were determined by the physical design of the existing vacuum system of PROTO II. The available space within the vacuum tank was limited and restricted. This was due to the fact that there were 8 radially positioned ports at 75 degrees from the z-axis. Outside the vacuum tank available space and positioning constraints were equally severe because of the placement and separation of the input-current feed lines around each port. These allowed placement of a 4.5-inch-diameter piece of apparatus no closer than 84 cm from the source outside the vacuum chamber.

Because of the physical constraints, the nominal Bragg angles of the metal multilayers had to be less than 11 degrees in order to prevent the multilayer placed 15 cm from the source from blocking other lines of sight and also to diffract the relevant x rays out the available 75-degree port. The constraints on the Bragg angle set the possible 2d-spacing of the metal multilayers. Specifically, for 1 keV radiation the 2d-spacing could not be less than 71.5 Å. Since it had been determined that two crystal holders for nominal Bragg diffraction at 5 and 10 degrees would be used in the spectrometers, the two multilayer 2d-spacings to be investigated were to be ~70 Å and ~140 Å. Tungsten-carbon, molybdenum-carbon, and palladium-carbon multilayers having the

required $2d$ -spacings were obtained from Troy Barbee of Stanford University and were used as the Bragg diffraction elements in all the time-integrate experiments. The room temperature x-ray properties of these multilayers can be found in Tables A1 and A2 in Appendix A.

In order for multilayers of different d -spacings to view the source at the proper incident angles, a method for alignment and positioning the multilayers had to be developed. A method was evolved that used an alignment tube connected to a ball joint. The ball joint and alignment tube are shown in Figure 23. Assembly was done by sliding the alignment tube inside the vacuum flange with a slip ring holding the ball joint socket against the seating lip. The alignment tube could then pivot about the ball joint and was pointed with the alignment ring. The alignment ring was mounted on the inside of the PROTO II vacuum chamber. The multilayer and its holder were held in place at the other end of the alignment tube. A photograph of the components of Spectrometer 2 is shown in Figure 23.

To align the spectrometer, a 2.54 cm-diameter portable laser was directly coupled to the alignment tube. The laser beam would reflect off the metal multilayer and would then shine into the vacuum chamber. By adjusting the position of the tube, the laser beam could

Figure 23. Photograph of the components of Spectrometer 2 used in the time-integrated experiments.

be directed onto the source position. The laser was removed after alignment had been completed.

Experimental Run

The experiments took place from 15 October 1984 to 17 December 1984. During that period the machine averaged four shots a week. Not all shots used neon gas. Some had xenon and some had krypton as the implosion gas. In addition, different targets of polyacrylic acid foams and parylene "soda straws" on which the gas puffs were imploded were used. These targets provided a variety of sources with different spectral properties and different total energy outputs.

During the first four shots the experiment was fielded. Spectrometer 1 at 13.5 degrees was found to be so long as to be an obstruction and to unbalance the top of the vacuum enclosure. The tube on which the spectrometer was mounted was therefore shortened. The distance between the source and the multilayer was then 150 cm.

In addition, Spectrometer 1 was experiencing debris problems. Hot gas as well as molten return-current wire was being blasted straight up the spectrometer pipe onto the control multilayer, destroying the prefilter on the way. A 75-degree port that had been previously assigned

to another experiment became available, and Spectrometer 1 was shifted to that port. The 75-degree port and the 13.5-degree port were different distances from the source, making it then necessary to lengthen the tube the spectrometer was mounted on. The debris problem was decreased further by placing a circular 2-cm inner-diameter baffle in the spectrometer tube at 86.4 cm from the source.

The change in port assignments also made it more likely that both spectrometers were looking at a similar cross section of the source. This reduced intensity variations due to different source-viewing angles. Spectrometer 1 was positioned 45 degrees azimuthally from Spectrometer 2. A revised schematic is shown in Figure 24.

Because the source characteristics exhibited shot-to-shot variation of intensity and continuum content, there were problems getting "clean" spectra of the neon resonance lines. Different prefilter and postfilter material combinations of aluminum, beryllium, parylene, aluminum oxide, parylene, Kimfol, and Kapton were tried to optimize the spectra. The best filter combination was determined to be one layer of 2 μ m-thick Kimfol plus 0.3 mils of aluminum foil as the prefilter and 4-5 layers of 2 μ m Kimfol and 0.5-mils-thick aluminum foil as the post

Figure 24. Revised schematic of the two multilayer spectrometers used at PROTO II.

filter for neon target shots. The transmission characteristics of this filter combination are shown in Figure 25.

Another problem encountered and solved was the determination of the proper x-ray film to be used. SB-5 and RAR 2497 x-ray films were used side by side and back to back to determine different contributions to background and signal. It was finally decided to use RAR 2497 in front and SB-5 in the back to give spectral ranges of 900 eV-1.8 keV for the RAR 2497 film and >3 keV for the SB-5 film. The energy response of the film was taken to be that of Henke et al. (1984a and b), and their prescribed processing procedures were strictly followed. Figure 26 gives the effective energy sensitivity of the final film configuration.

After the multilayers were exposed to PROTO II, they were taken back to the laboratory, and their x-ray reflection properties were remeasured as a function of angle at $\text{Cu } L_{\alpha}$ wavelength. All the multilayers that had been used in Spectrometer 2 (only 15 cm from the source) were so scorched and covered with debris that they no longer had any Bragg diffraction properties. The debris was hot gas, molten return-current wires, and stainless steel. Attempts were made to clean the debris off the multilayers but to no avail. Those multilayers that had

Figure 25. Transmission of "best" filter combination of 8 μm of Kimfol and 0.5 mil of Al as the postfilter and 2 μm of Kimfol and 0.3 mil of Al for the prefilter.

Figure 26. Spectral sensitivity of final film configuration used in the multilayer spectrometers.

been used in Spectrometer 1, though they had a few marks from hot gas, were remeasured to have the same reflection properties as before. The multilayers used in Spectrometer 1 could therefore be used again.

A summary description of the useful shots for the time-integrated run is found in Table 2. Shots #1789, #1805, and #1806 used the molybdenum-carbon, long d-spacing multilayers that required the smallest Bragg angle for diffracting the neon resonance lines. For these shots, each spectrometer detected the presence of two spectral lines. Preliminary identification based on the position and spacing of the two lines was made to be the hydrogen- and helium-like resonance lines observed with the KAP curved-crystal spectrograph as shown previously in Figure 11 of Chapter II-1. The spectral lines of Spectrometer 2 were very large and widely spaced compared with those of Spectrometer 1. This was due to the difference in the separation between the multilayer and the detector in the two spectrometers. In addition, the large width of the spectral lines on both spectrometers was due to the finite extent of the source. The diameter of the source was 2-5 mm depending on the shot, and not the expected 2 mm. The diameter of the source was determined from the pinhole photographs.

Shot #1798 was the only shot for which good data

TABLE 2. SUMMARY OF USEFUL TIME-INTEGRATED NEON GAS SHOTS.

Shot Number	Target	Bolometer		Multilayer		2d o (A)
		Line Yield (kJ)	Total Yield (kJ)	Spectrometer 1 (far)	Spectrometer 2 (near)	
1796.	CH straw	10.3	21	83-021-II	.5 of 83-021-I	72
1798	Ti-coated straw	12.2	44	83-023a-IV	.5 of 83-023A-V	116
1805	foam	8.8	30	83-023A-II	.5 of 83-023A-I	116
1806	foam	7.0	18	83-023A-II	.5 of 83-023A-III	116

were obtained using a $70\text{-}\text{\AA}$ multilayer, and that was only on Spectrometer 1. This was because the shorter d -spacing multilayers required the larger angles. Setting the multilayer of Spectrometer 2 at these larger angles proved to be difficult, and the line of sight to the source could have been blocked by the return current posts.

Conclusions that could be drawn from the time-integrated data were that the spectral lines could indeed be recorded for the larger $2d$ -spacing multilayers and that the basic design of the spectrometers was sound. In addition, these data gave needed rough intensity numbers and physical parameters with which to design a time-resolved detector system.

CHAPTER II-3

TIME-RESOLVED EXPERIMENTS

The Experimental Design

The purpose of this phase of the investigation was to observe changes in x-ray reflectivity properties of metal multilayers as a function of time and irradiance. If the multilayer were heated by the incident flux, a possible angle shift in the reflected line profile due to thermal expansion of the layers, as well as a possible widening of the diffraction pattern due to decreasing order among the layers, might be expected.

As previously mentioned, the nominal duration of the neon resonance x-ray lines was 20 ns. If 10 time frames or bins were necessary to observe the expected changes, a system with approximately 2-ns time resolution was needed. The spatial requirements for detecting changes in the angular position or widths of the x-ray diffraction pattern, that is, the spectral lines, could be determined from the time-integrated data. Since the width of a line at the Spectrometer 2 detection plane was observed to be 2.5 mm, for a minimum of 10 resolution elements 250- μ m-wide resolution elements were needed. These temporal and spatial resolution requirements could be met with a fluorescer-fiber optic-visible streak

camera system.

To determine whether a fluorescer-fiber optic-streak camera system was a viable detector system, it was necessary to calculate whether there would be a sufficient light signal. A rough calculation was done as follows.

The proposed configuration and parameters necessary to calculate the flux through the detector system are shown in Figure 27. The source temporal FWHM was taken to be 20 ns and to have 5 kJ of total energy in each line at 1022 eV and 922 eV. This took into account the increased energy yields seen in the time-integrated run. The intensity available, I_p , is given by the equation

$$I_p = \frac{E_{\text{line}}}{4\pi \Delta t E_{\text{photon}}} \quad (27)$$

where E_{line} is the total energy in the line, Δt is the x-ray pulse width, and E_{photon} is the photon energy of the line. Therefore,

$$I_{p/1022} = \frac{5 \text{ kJ} \times 1000 \text{ J/kJ}}{4\pi \text{ sr} \times 1022 \text{ eV/ph} \times 1.6 \times 10^{-19} \text{ J/eV} \times 20 \times 10^{-9} \text{ s}} \\ = 1.216 \times 10^{26} \text{ ph/sr-s} , \text{ and}$$

$$I_{p/922} = \frac{5 \text{ kJ} \times 1000 \text{ J/kJ}}{4\pi \text{ sr} \times 922 \text{ eV/ph} \times 1.6 \times 10^{-19} \text{ J/eV} \times 20 \times 10^{-9} \text{ s}} \\ = 1.349 \times 10^{26} \text{ ph/sr-s} .$$

The flux at the fluorescer was calculated by the

Figure 27. Diagram defining parameters necessary to calculate the flux through the fluorescer-fiber optic-streak camera system.

equation

$$F = \frac{I_p d\psi d\theta C_d(\theta_B) \cos(\alpha)}{dX dH} \quad , \quad (28)$$

where $d\psi$ is the angular "height" of the multilayer intercepted at the detection plane, $d\theta$ is the angular "length" of the multilayer intercepted at the detection plane, $C_d(\theta_B)$ is the peak reflectivity of the crystal function, dX is the resolution width of the line at the detection plane, and dH is the resolution height at the detection plane. The resolution width, dX , was taken to be the physical width of the lines observed by Spectrometer 2 during the time-integrated experiments, that is, 3 mm. The resolution height, dH , was taken to be the height of the film exposed in Spectrometer 2 during the time-integrated run, that is, 1.905 cm. The angles $d\psi$ and $d\theta$ were calculated according to the diagram in Figure 28 to be 0.0227 rad and 3.58×10^{-3} rad, respectively. Nominal reflectivity numbers for the peak of the crystal function, $C_d(\theta_B)$, were extrapolated from laboratory measurement to be

$$C_d(\theta_B) = 0.04 \text{ at } 1022 \text{ eV and}$$

$$C_d(\theta_B) = 0.03 \text{ at } 922 \text{ eV.}$$

Therefore, the flux at the fluorescer for the two lines was calculated to be

$$F_{1022} = \frac{1.216 \times 10^{26} \text{ ph/sr-B} \times (0.0227 \times 3.57 \times 10^{-3}) \text{ sr} \times .04}{0.3 \text{ cm} \times 1.905 \text{ cm}} \quad ,$$

Figure 28. Derivation of $d\psi$ and $d\theta$.

$$\begin{aligned}
 &= 6.897 \times 10^{20} \text{ ph/cm}^2\text{-s} \quad , \quad \text{and} \\
 F_{922} &= \frac{1.349 \times 10^{26} \text{ ph/sr-s} \times (0.0227 \times 3.57 \times 10^{-3}) \text{ sr} \times .04}{0.3 \text{ cm} \times 1.905 \text{ cm}} \\
 &= 5.739 \times 10^{20} \text{ ph/cm}^2\text{-s} .
 \end{aligned}$$

The light intensity at the other side of the fluorescer is given by the equation

$$I_s = C_F F , \quad (29)$$

where C_F is the conversion efficiency of the fluorescer. The conversion efficiency of a 2-mil-thick fluorescer was approximated (Lyons and Lier, 1975) for one keV photons to be 4.974×10^{-4} . Therefore for the two energies

$$\begin{aligned}
 I_{s/1022} &= 4.974 \times 10^{-4} \text{ sr}^{-1} \times 6.897 \times 10^{20} \text{ ph/cm}^2\text{-s}, \\
 &= 3.43 \times 10^{17} \text{ ph/cm}^2\text{-sec-sr}, \text{ and} \\
 I_{s/922} &= 4.974 \times 10^{-4} \text{ sr}^{-1} \times 5.739 \times 10^{20} \text{ ph/cm}^2\text{-s}, \\
 &= 2.85 \times 10^{17} \text{ ph/cm}^2\text{-sec-sr} .
 \end{aligned}$$

The flux, F_t that is within the acceptance angle of the fiber is given by

$$F_t = \sim I_s \times (N.A.)^2 \times \pi , \quad (30)$$

where $N.A.$, the numerical aperture of the fiber, was taken to be 0.26. Therefore,

$$\begin{aligned}
 F_{t/1022} &= 3.43 \times 10^{17} \times 0.2124 = 7.285 \times 10^{16} \text{ ph/cm}^2\text{-s-sr}, \text{ and} \\
 F_{t/922} &= 2.85 \times 10^{17} \times 0.2124 = 6.063 \times 10^{16} \text{ ph/cm}^2\text{-s-sr} .
 \end{aligned}$$

A rough number for the attenuation in a fiber is ~44 dB/km; that is, for a 50-m fiber there would be a loss of 2.2 dB, which is equivalent to 60.2 percent

transmission. Therefore, the flux at the other end of the fiber, F_{sc} , would be

$$F_{sc/1022} = 0.602 \times 7.285 \times 10^{16} = 4.38 \times 10^{16} \text{ ph/cm}^2\text{-s, and}$$

$$F_{sc/922} = 0.602 \times 6.063 \times 10^{16} = 3.65 \times 10^{16} \text{ ph/cm}^2\text{-s .}$$

A "rule of thumb" number is that at least $10^{15} \text{ ph-cm}^{-2}\text{-s}^{-1}$ are required to exceed the threshold sensitivity of the streak camera. This calculation indicates that there would be a signal about 40 times this threshold; however, there were no corrections for filters or reflection losses at interfaces. According to the results of this calculation, then, a fluorescer-fiber-streak system would work if careful attention were paid to possible signal losses.

The Fiber Bundle

The available optical fiber was the Corning DBF Short Distance fiber. Its advertised characteristics were attenuation of 4 db/km at 850 nm and 2 db/km at 1300 nm with a bandwidth of 200 MHz/km at both wavelengths. The fiber had an 85- μm -diameter core and an outer diameter of 125 μm . In order to get the signal from the fluorescer to the electromagnetic impulse (EMI) protected streak camera, the length of the bundle had to be 47 m. Attenuation losses in the fiber begin to become significant at this length. EG&G, Las Vegas Operations (LVO) measured

the attenuation of the DBF fiber used in making the fiber bundle as a function of wavelength, and their results are shown in Figure 29. Their Optical Multichannel Analyzer System could not go below 419 nm; thus, extrapolating to the wavelength of the peak of emission of NE111 gives approximately 66 dB/km or a loss of 30 percent for a 47-m-long fiber. This is 8 percent more than had been used in the threshold calculation. In addition EG&G, LVO measured the fiber's numerical aperture for two different lengths of fiber to be 0.24 and 0.25.

The time-integrated data were used to determine the physical configuration of the fiber bundle. The major constraint to the number of fibers that could be used to cover the two spectrometers' detection planes was the size of the streak camera's photocathode. A large photocathode was needed. An RCA-tube-based camera with a 3-cm-diameter photocathode was available, and the fiber bundle was designed with this in mind.

The two spectral lines detected with Spectrometer 2 during the time-integrated experiments were approximately 3 mm wide, and separated by 6-7 mm. By comparing all available data, it was determined that a bundle that had two sets of 56 fibers separated by 6 mm would be sufficient to cover these two lines if the position of the fiber bundle could be adjustable for different d-

Figure 29. Spectral attenuation as a function of wavelength of the DBF fiber for three different wavelength ranges.

spacing multilayers. The linear distance at the streak camera end would then be $2 \times 56 \times 125 \text{ } \mu\text{m}$, or 14 mm.

The lines on Spectrometer 1 were much closer together. By analyzing the time-integrated data, it was concluded that 64 fibers were enough to cover the spectral lines if the bundle's position could be adjusted for different d-spacing multilayers. The linear distance at the streak camera for this array would therefore be the same as at the fluorescer end, that is, 8 mm. Figure 30 shows the configuration of the fiber bundle.

In order to position the fiber bundle arrays at each spectrometer, two holders were designed on optical linear positioning stages. The holder-stage of Spectrometer 1 was positioned directly with a micrometer. The holder-stage of Spectrometer 2 could not be positioned directly because of the close tolerances the spectrometer tube had with the pulse lines of PROTO II. A right angle gear drive was therefore designed to position the holder-stage of Spectrometer 2. Photographs of the holder-stages are shown in Figures 31 and 32 for Spectrometer 1 and Spectrometer 2, respectively. An important design consideration was the necessary capability of maneuvering the fiber bundle face flat up against the vacuum face-plate window for most efficient coupling.

Figure 30. Configuration of the fiber bundle ends.

Figure 31. Photograph of the fiber bundle holder-stage assembly for Spectrometer 1.

Figure 32. Photograph of the fiber bundle holder-stage assembly for Spectrometer 2.

The usable part of the 3-cm streak camera photocathode was the center ~2.7 cm. The length of the fiber arrays needed to cover the two spectrometers' detection planes was 2.2 cm, leaving 0.5 cm that could be used for calibration fibers.

The Fluorescer

There were three main considerations for determining which fluorescer to use. The first consideration was that the fluorescer was to be used in a vacuum; therefore, a solid fluorescer was deemed most practical within the imposed time constraints. The second consideration was the need to satisfy the time-resolution requirement. The final consideration was the availability of the fluorescer chosen.

The two most commonly used fluorescers for photons in the keV energy range are NE111^C and NE102^C. Their spectral output has been studied extensively (Pronko et al., 1978 and 1979). Their intrinsic temporal widths have been measured (EG&G, 1981) to be 1.9 ns for NE111 and 2.9 ns for NE102. It is important to note that the total integrated spectral output of NE111 is approximately twice that of NE102.

In addition to the intrinsic temporal FWHM of the fluorescer itself, the energy dispersion properties of the fiber to be used had to be considered. Typical

fiber optic dispersion numbers (Ogle, 1985) at the two energy peaks of the respective fluorescers are 50.5 ps/nm-100ft and 34 ps/nm-100ft of fiber for NE111 and NE102 light, respectively. Taking the geometric mean of the intrinsic FWHM and the dispersion in a 50-m fiber for each fluorescer gives

$$\text{FWHM}_{\text{NE111}} = ((1.9 \text{ ns})^2 + (3.9 \text{ ns})^2)^{1/2} = 4.33 \text{ ns and}$$

$$\text{FWHM}_{\text{NE102}} = ((2.9 \text{ ns})^2 + (1.6 \text{ ns})^2)^{1/2} = 3.31 \text{ ns .}$$

In the above formula the largest component of the FWHM for NE111 is the dispersion term, while for the NE102 it is the intrinsic FWHM. Therefore, considerable gains in the time resolution could be made if the dispersion term of the NE111 could be decreased by using an interference filter. A BARR^C interference filter was available that had been specifically designed to peak near the NE111 wavelength and to limit the FWHM of its radiation to 20 nm. Dr. Donald Casperson of Los Alamos National Laboratory had run a spectrophotometer scan on this filter, and this is shown in Figure 33. The integrated transmission of the interference filter is 0.21 over the NE111 emission band. The subsequent dispersion contribution using the interference filter was then only 1.56 ns. This gave for the resultant effective temporal FWHM,

$$\text{FWHM} = ((1.9 \text{ ns})^2 + (1.56 \text{ ns})^2)^{1/2} = 2.45 \text{ ns.}$$

Figure 33. Spectrophotometer scan of BARR interference filter showing percent transmission as a function of wavelength.

The combination of the BARR filter and the NE111 fluorescer gave the nearest values to the previously stated temporal resolution requirements using available materials.

The problem of getting the light that is converted by the fluorescer out of the vacuum and into the fiber bundle had to be taken into consideration. This was done by using a fiber optic faceplate as the vacuum window and "butt" coupling the fluorescer to the faceplate. The faceplate obtained was reported to have a transmission of 25% (Galileo Electro-Optics Corp., 1981), with 5.8- μm outer diameter fibers, a numerical aperture of 1.0, and a thickness of 4.1 mm.

The fiber bundle was designed to cover each spectral line of Spectrometer 2 with 8 fibers. The addition of the fluorescer, the interference filter, and the faceplate necessitated re-examining the spatial resolution of the system. The thicker the fluorescer and interference filter, the larger the width of a signal a fiber would see. Conveniently, pieces of reported 50- μm -thick NE111 were available. The Barr interference filter was also reported to have a thickness of 50 μm .

The configuration proposed and the contributing factors to the spatial resolution are depicted in Figure 34. Even though the numerical aperture of the fiber

Figure 34. The effects of the fluorescer and interference filter on the spatial resolution, Δx , of the system. The spot size on the photocathode is less than the outer diameter of the fiber; therefore, the spatial resolution is determined at the fluorescer end of the system.

faceplate is 1.0, the effective numerical aperture of the system is determined by the component with the smallest numerical aperture. In this case it is the numerical aperture of the fibers in the fiber bundle, 0.245. Since the fiber faceplate is made up of 5.8- μm fibers, it takes 14.66 faceplate fibers to cover the diameter of a single fiber of the bundle. The amount of light that is collected by one fiber in the bundle is actually determined by the next nearest integer value, or 15 fibers in the faceplate. Since those 15 fibers have an effective numerical aperture of 0.245, then, at the top of the fluorescer the spot size will be 111.5- μm diameter. This 111.5- μm diameter is smaller than the outer diameter of the fiber in the fiber bundle. On the other end, the bundle is "butt" coupled directly to the interference filter and the interference filter is coupled to the streak camera photocathode. The spread at the photocathode surface using the numerical aperture of 0.245 is therefore 110.3 μm . This is also less than the outer diameter of the fibers in the bundle as well as the spread at the top of the fluorescer. For this reason, the spatial resolution of the system is determined by that at the fluorescer, or input end.

Because the fluorescer was to be so thin, any high-energy component (second or third order of the multi-

layer) of the incident spectrum would not be completely absorbed by the fluorescer but would be partly transmitted to the faceplate itself. There was some concern that the faceplate would also fluoresce, contributing to a background signal. However, since the BARR filter was on a glass cover slip, placing it directly between the fluorescer and the faceplate might lower any fluorescent background if the cover slip had a lower efficiency than the faceplate. These concerns led to a series of measurements using Ti K_{α} x rays as a source for determining the difference in fluorescent yields. From these data it was concluded that it was best to put the fluorescer directly in front of the faceplate and to put the interference filter outside the vacuum system to minimize the background signal.

Fast Valve

As described in Chapter II-2, the standard multilayer in Spectrometer 1 continually had damage due to debris. Since the debris arrived later than the x rays, a fast valve could be used to protect the multilayer from the debris and still pass the x-ray signal. A model 130 fast valve from Spectral Precision, Inc., with a 1-cm X 2-cm aperture and a 1-ms closing time was obtained for this purpose. A watertight aluminum box with o-ring

seals was used to protect the electronics on the valve itself. In addition, the power cords to the valve were shielded inside a grounding strap and were wrapped several times around ferrite toroids to protect the fast valve from the electromagnetic impulse which occurred when PROTO II was fired. The valve had an insertion length of 2 inches and was placed immediately in front of the multilayer holder assembly where the manual valve had been during the time-integrated run.

The Streak Camera System

The streak camera system, built and supported by EG&G, Los Alamos Operations (LAO), was an RCA-tube-based-modular streak camera. The photocathode was an S-20 type and the phosphor was P-20. A type II micro-channel plate image intensifier (MCP) was butt-coupled to the streak camera, and Polaroid Type 57 and Kodak RXP films were used in the accompanying filmbacks. The resultant dynamic resolution of the streak camera was 10 lp/mm. The camera was used mostly at 2.6 ns/mm. Figure 35 shows a photograph of the streak camera.

The camera was supplied with an optical impulse generator and an optical comb generator. The optical comb generator emitted 4 mW of 812-nm light down an attached optical fiber every 2 ns. This comb signal was

Figure 35. The EG&G streak camera. Shown here are the components of the film back, the microchannel plate (MCP), the streak tube housing, and the fiber optic bundle mount.

then split into three fibers by a fiber splitter to bracket each set of data with timing marks. The optical impulse generator emitted 15 mW of 823-nm light down an attached fiber at the prescribed set time.

Timing

Determining the correct timing sequence took some care since the optical path of the signal was the same as that of the time calibration signals. The major factors that had to be accounted for in the timing sequence were the delay times associated with the streak camera deflection and turn on, the MCP's delay, and the delay in the comb and impulse generators. Other factors included the jitter in the line switches and the variable implosion times. A schematic of the timing for the streak camera is shown in Figure 36. The timing points of interest at the PROTO II machine end are shown in Figure 37.

Overall Setup

The main difference between the time-integrated experimental system and the time-resolved setup is the replacement of the filmbacks with the fiber-fluorescer-streak camera detector system described above. The multilayer holders and alignment procedures for the Spectrometer 2 multilayer were all the same.

Figure 36. Schematic of the streak camera timing sequence.

Figure 37. X-ray, signal, and trigger paths of the two multilayer spectrometers.

One change was necessary in order to minimize the length of fiber necessary to reach the screen room and to decrease the possibility of entanglement with people and equipment. Both spectrometers were shifted 135° to the east of their previous placement, to the other side of the vacuum chamber closer to the screen room.

In order to protect the fiber bundle and prevent spurious light from contributing to the signal, the fiber bundle was fed through a curved stainless steel pipe, then a flexible copper bellows, and then through a conduit all the way to the screen room. Photographs of the two time-resolved spectrometers as fielded on PROTO II are given in Figures 38 and 39.

Experimental Run

The time-resolved experiments took place from 21 February 1985 to 18 April 1985. The Proto II experimental team's emphasis for this run was the implosion of neon gas onto a variety of targets. Different targets of metal-doped polyacrylic acid foams and metal-coated parylene "soda straws" were used. At the beginning of the run, it was necessary to use several shots to set the timing of the streak camera and to adjust the filtration. This was complicated by low-yield shots and the lack of any data visible on the film.

Figure 38. Photograph of the two time-resolved multi-layer spectrometers as configured during the run.

ADJUSTMENT FOR
FIBER BUNDLE

SPECTROMETER 2

FIBER BUNDLE
PROTECTION

FAST
VALVE

MAGNETS

POSITION OF
MULTILAYER

ADJUSTMENT FOR
FIBER BUNDLE

SPECTROMETER 1

Figure 39. Photograph of the PROTO II vacuum chamber, multilayer spectrometers and the associated radial diagnostics.

SPECTROMETER 2

SPECTROMETER 1

**NOZZLE & RETURN
CURRENT POSTS**

**MULTILAYER HOLDER
& ALIGNMENT BAR**

Initial filters for Spectrometer 1 were a post-filter of a 4- μ m Kimfol film with a 800- $\text{\AA}$ Al coating and a 2- μ m Kimfol film with a 400- $\text{\AA}$ Al coating for the pre-filter. For Spectrometer 2 the initial filters were a postfilter of 4- μ m Kimfol film with a 800- $\text{\AA}$ Al coating and a prefilter of 5000- $\text{\AA}$ Al foil.

During the pump down of Shot #1857 the postfilter of Spectrometer 2 fell off and no prefilter had been in place; therefore, data obtained were of the white light pulse. This gave a baseline to determine both the timing of the streak camera and the filtration. Because the filters were found to be too thick, they were cut down to an approximate total thickness of 8000 $\text{\AA}$ of Al. The postfilter on Shot #1861 had pinholes, causing the streak record to show both the white light and the x-ray signal. This confirmed that the x-ray signal was indeed being detected during the run.

An additional timing problem that had to be worked out was that of the fast valve. The filter and/or multilayer was damaged in Spectrometer 1 when the fast valve was not triggered soon enough. The timing was determined at just about the point in the run where the fast valve electronic box consistently began to take on water. The electronics housing had been constructed out of aluminum and during the course of the shots had

developed hundreds of tiny cracks in its welds due to the violence of the machine firing. The valve did not operate when the electronics were filled with water. Attempts were made to reweld the box and to seal it with silicon sealant. All the attempts failed. The fast valve was therefore inoperable for the rest of the run, and the debris problem continued.

Another problem that was encountered during the run was that when the machine was fired, there was so much torque on the threaded joint of Spectrometer 1 that it broke the weld. This breakage allowed water into the system behind the fiber faceplate, getting the fiber bundle end and holder stage wet. This problem was solved by welding two nuts to the outer threaded piece and bolting it to the other threaded piece. The nuts can be seen in Figure 31.

Depending on the target, the current return posts were of different sizes. Unexpectedly, the thicker half-inch-diameter posts blocked the nose of Spectrometer 2. This prevented acquisition of data from Spectrometer 2 for those shots.

During the course of this run, positive streak camera data were obtained for 9 out of 19 x-ray producing shots.

Data

A general summary of the time-resolved-data shots and the accompanying Sandia data from the diagnostics that were discussed in Chapter II-1 is given in Table 3.

For each shot, the streak camera record on RXP film consisted of a step wedge, timing combs, an impulse, and the data. Figure 40 shows a print of the streak record from Shot #1863. The signal from the comb generator consists of the three columns of white dots. Each dot is separated by two nanoseconds. The step wedge is put on each film such that a specific film density can be related to a known energy density.

The step wedge is exposed onto the film with a spectrum that simulates the light emitted from the P-20 phosphor of the streak camera system. Each of the 26 steps is obtained by placing different neutral density filters between the film and the light source. The step wedge used was constructed by M. A. Palmer at Sandia, and its optical and energy density values are given in Table 4.

All streak camera data were digitized by EGG (LAO) with a Perkin-Elmer PDS Microdensitometer. For data analysis, the step wedge was digitized as follows. For each step of the wedge, a 512 X 19 pixel array was taken using a 42- μ m X 42- μ m square aperture with a 10- μ m step over.

TABLE 3. SUMMARY OF TIME-RESOLVED DATA SHOTS.

Shot Number	Target	Multilayer		XRD	Bolometer	KAP Crystal	Pinhole
		Spectrometer 1 (Close)	Spectrometer 2 (Far)				
1858	V-foam	weak	weak	4	good	weak	good
1860	V-foam	weak	weak	6	good	weak	good
1861	V-foam	pinholes	weak	5	good	good	good
1862	V-foam	weak	weak	6	good	good	good
1863	none	good	good	2	good	good	good
1871	V-foam	weak	-	6	good	good	good
1872	V-foam	good	good	5	good	good	good
1874	Cl-foam	weak	weak	6	good	good	good
1875	Cu/Al- foam	-	good	6	good	-	good

Figure 40. Print of streak record of Shot #1863 showing data, combs, impulse, step wedge, and the space that separates the two sections of fiber of Spectrometer 2.

TABLE 4. DENSITIES OF THE STEP WEDGE WITH CORRESPONDING VALUES OF EXPOSURE.

Step Number	Step Density	$\text{Log}_{10} \text{EXP}$ (erg/cm^2)	Step Number	Step Density	$\text{Log}_{10} \text{EXP}$ (erg/cm^2)
1	0.04	0.5069	14	2.10	-1.5531
2	0.20	0.3469	15	2.26	-1.7131
3	0.35	0.1969	16	2.43	-1.8831
4	0.51	0.0369	17	2.60	-2.0531
5	0.66	-0.1131	18	2.77	-2.2231
6	0.82	-0.2731	19	2.93	-2.3831
7	0.98	-0.4331	20	3.10	-2.5531
8	1.14	-0.5931	21	3.24	-2.6931
9	1.30	-0.7531	22	3.40	-2.8531
10	1.45	-0.9031	23	3.55	-3.0031
11	1.61	-1.0631	24	3.72	-3.1731
12	1.78	-1.2331	25	3.87	-3.3231
13	1.94	-1.3931	26	4.02	-3.4731

The optical density is defined as the negative base 10 log of the transmission observed through the film. The optical densities determined from the step wedge are then used to produce a "lookup" table of density versus exposure.

For the data, the entire streak camera record was digitized with an array of 512 X 512 pixels, using a 42- μ m X 42- μ m-square aperture with a 50- μ m stepover. The array was then "straightened" by computer with respect to the combs. By the use of a Comtal system, an average over any number of columns (distance) or rows (time) could be taken and plotted. The time scale is determined by the number of pixels between the comb dots. This averaging process is known as "compressing the streak." The compressed streak is what will be compared with the calculations.

Figure 41 shows such an average for Shot #1863 for corresponding signals of the same feature for each spectrometer. The data have been smoothed using the adaptive filtering code AWARE (Hodson et al., 1981). AWARE takes a weighted average of the data points according to the steepness of the data. The signal from Spectrometer 1 is larger than that of Spectrometer 2, in part because Spectrometer 1 exhibits higher background exposure due to its more straight-through line of sight.

Figure 41. Compressed streak from Spectrometers 1 and 2 for Shot #1863. Data were smoothed in exposure space using AWARE adaptive filtering code.

In addition, the compressed streak of Spectrometer 2 is over more pixels than Spectrometer 1 causing the average exposure to be less. The time history of the signal from Spectrometer 1 has a FWHM of ~ 25 ns, which is in agreement with the bolometer signal. The signal from Spectrometer 2 exhibits a FWHM of only ~ 8 ns and falls off very rapidly, indicating that the multilayer reflecting surface was destroyed before the peak of the radiation pulse.

Discussion

Calculations presented at the beginning of this chapter indicated that signal levels of ~ 40 times the threshold level of the streak camera system were expected to be observed and that distinct lines were expected to be seen. However, as the data in Figure 39 indicated, the signals for both spectrometers were very weak and the traces were "fuzzy" without distinct lines. Post-measurements indicate that the problem of low-signal output was in part due to the impurity of the fluorecser. The problem of indistinct lines was determined to be due to poor spectral and spatial resolution of the system.

Fluorecser conversion efficiency. The NE111 fluorecser used was obtained in early 1982 and had a 2-

percent doping of benzophenone. Because the dopant easily leaves the fluorester, as evidenced by the smell of a doped fluorester, it was thought by this investigator and others that a 3-year-old, 50- μ m sample would have lost all its dopant. The dopant is normally used to enhance the time response of the fluorester, but in return it drastically lowers the fluorester's conversion efficiency, contributing to a lower signal output.

The first indication that the presence of dopant was the cause of the low signals was that post-measurements of the conversion efficiency showed disagreement with the reported values of pure NE111 (Lyons and Lier, 1975; Lyons et al., 1976).

Direct measurements of the NE111 conversion efficiency were done at O K_{α} and Cu K_{α} wavelengths. The measured conversion efficiency at O K_{α} (524.9 eV) was 1.74×10^{-3} W/W, which is the same as the reported value. The value at Cu K_{α} (8047.8eV) was determined to be 1.25×10^{-3} W/W compared with a reported value of 5.0×10^{-3} W/W, a factor of 4 low. These measurements are consistent with the hypothesis that there was a dopant concentration gradient in the NE111 used. The measurements with the shallow penetrating O K_{α} x rays gave a characteristic conversion efficiency of undoped NE111, while the measurements with the deeper penetrating Cu K_{α} x rays

gave a low conversion efficiency consistent with a high dopant concentration.

To further support the gradient hypothesis, measurements were done to determine the time response of two pieces of the 50- μm NE111 and a 10- μm sample that was from the same batch as the fluorecser used in the time-resolved experiments. The measurements were done by Steve Lutz of EG&G, Santa Barbara, using a 50-ps electron pulse to excite the fluorecser and a Varian micro-channel plate as the detector. This kind of measurement is of the bulk properties of the fluorecser; in other words, it gives an indication of the average amount of dopant in the sample. Table 5 shows the results of these measurements, and includes the observed FWHM as well as an estimated unfolded FWHM that accounted for the 0.184-ns detector FWHM.

TABLE 5. TIME RESPONSE MEASUREMENTS OF NE111 SAMPLES.

Sample	Observed FWHM (ns)	Unfolded FWHM (ns)
Pure	-	1.23
10 μm	0.876	0.855
50 μm (a)	0.342	0.285
50 μm (b)	0.320	0.258

These results indicate that the 10- μm sample has less dopant than the 50- μm sample but is not pure since its measured FWHM is less than that of the pure NE111 sample reported by Lyons and Stevens (1974). The 50- μm sample has even more dopant, as evidenced by its very fast time response. These measurements support the hypothesis that there is a gradient of dopant in the fluorescer used.

Since benzophenone is made up of the same constituents as NE111 itself, the conversion efficiency as a function of energy has the same shape for a homogeneously doped sample as that of a pure sample (Steve Lutz, 1986). Therefore, the conversion efficiency as a function of energy of a gradient-doped sample would be the product of a decaying amplitude function of energy, determined by the gradient, and the conversion efficiency of a pure sample.

Spatial resolution. During the course of the time-resolved run, distinct spectral lines were not seen in the streak camera data. When the components of the spatial resolution argument presented at the beginning of this chapter were reviewed, the following was found. First of all, the fluorescer was 63.5- μm thick and not 50 μm , and secondly, the reported 50- μm thick interference filter was in actuality 149.1- μm thick. Figure 42 shows

Figure 42. Determination of spatial resolution of the fluorescer-fiber bundle-interference filter system with measured thicknesses. The spot size on the streak camera's photocathode is greater than the outer diameter of the optical fiber.

how these thicknesses contribute to the spatial resolution and can be compared with Figure 34. The most significant effect of these thicknesses is that of the interference filter. With a numerical aperture of 0.245 across the 149.1- μ m filter, the output spot size is 160 μ m in diameter. This spot size is greater than the outer diameter of the fiber in the bundle, signifying that the signals from adjacent fibers will overlap. In other words, spatial resolution is ambiguous in this case. This ambiguity and the very low signals on Spectrometer 2 contributed to the indistinct streaks.

Spectral resolution. The experiments were originally designed such that the incidence angles of the multilayers would be nominally 5 and 10 degrees. The 10-degree incidence angle would have given a cleaner line spectrum because there would be a smaller specular reflection component of the signal. However, the anode posts that were used during the run obstructed the line of sight of Spectrometer 2 when the 10-degree multilayers were used.

The theoretical R vs. E curve of the tungsten-carbon multilayers used on the time-resolved run is shown in Figure 43. The incidence angle was taken to be 6.25 degrees. Figure 43 shows explicitly the low-energy specular reflection component of the x-ray reflectivity.

Figure 43. Theoretical R vs. E curve for a tungsten-carbon multilayer of $2d=135\text{\AA}$ at an incidence angle of 6.25 degrees.

For the time-integrated run, distinct spectral lines were observed because the sensitivity of the x-ray film was so high that it made it possible to use thick filters to attenuate the spectral component of the reflectivity. However, the fluorescer-fiber optic-streak camera detector system was so insensitive that this was not possible, and in fact only very thin aluminum postfilters could be used.

The problems with the fluorescer conversion efficiency, the spatial resolution, and the spectral resolution imply two things. First, absolute comparison of the intensity recorded by the fluorescer-fiber optic-streak camera system and that calculated cannot be made. However, comparison of time history and relative intensity comparisons can still be made. Secondly, any information of the rocking curve of the multilayer samples has been washed out with the spatial and spectral resolution problems; however, approximate peak reflection properties can still be determined.

CHAPTER II-4

THE INCIDENT SPECTRUM

Data from the two time-resolved multilayer spectrometers give information relative to the changes in the Spectrometer 2 multilayer reflection properties with respect to the control multilayer in Spectrometer 1. In order to determine at what flux levels the observed changes occurred, knowledge of the incident x-ray spectrum is necessary. Additionally, the incident spectrum must be known in order to calculate the physical deterioration of the multilayer and its corresponding reflection properties before a direct comparison with the experimental results can be made. To determine this x-ray flux, it is necessary to extract the spectral characteristics from the data provided by the 6 XRD detectors fielded by R. B. Spielman and S. F. Lopez.

The process of unfolding a spectrum is not an exact science since it is possible to get several answers that are all equally "correct." The inherent time resolution of the multilayer experimental system was 2.4 ns, giving an upper bound for the time steps necessary for the calculations.

The following procedure was implemented to obtain a representation of the incident spectrum. X-ray diode

traces were obtained from R. B. Spielman. Each XRD trace was then smoothed using the adaptive filtering code AWARE (Hodson et al., 1981). The ratio of the RMS standard deviation of the smoothed curve and the peak of the smoothed curve was taken to be the uncertainty in the XRD signals. By this means, each signal trace was assigned an uncertainty. For each shot, a table of times for analysis was made. These tables included the times of the peaks observed on the six channels as well as additional times at appropriate intervals, depending on the slope of the signal.

The signals for a particular time and their corresponding uncertainties were input into the code SHAZAM (Shirk and Hoffman, 1985). For each time, SHAZAM folds an assumed initial spectrum with a set of detector responses and calculates a resultant current signal for each detector. These current values are then compared with the observed current values. The spectrum is then adjusted according to a weighting scheme determined by how far off the calculated current of a detector is from the measured value and its corresponding uncertainty. New currents are calculated for the adjusted spectrum and the process continues.

The XRD responses were taken to be those presented earlier in Figures 17 and 18. The source size was

approximated from the pinhole photographs taken at 75 degrees from the z -axis of the plasma. The initial "guess" was constructed by using the thin-film bolometer yields to determine a temperature for a blackbody continuum and to determine the line strengths of the two neon resonance lines. This initial guess was constructed in the same way as the incident spectrum calculated in Chapter II-1 for the rough heating calculations.

For each time, the code was allowed to run until the χ -square parameter did not change more than one part in 1000, or until the uncertainties of the channels were satisfied. To ensure that the initial guess did not force the code to give an erroneous result, a second initial guess of a flat spectrum that cut off at 1.3 keV was input into the code. This was to obtain a cross check of whether the trends seen in the results from the first guess were again exhibited. SHAZAM's ability to match detailed spectral features is limited by the detector responses. However, it is very good at matching total yields. An example of the spectrum unfolded by SHAZAM is shown in Figure 44.

Post-Calibration of XRD Detectors

The unfolded XRD spectrum was integrated over time and energy to determine the total energy yield to allow

SHOT 1872

Figure 44. Deconvolved spectrum from XRD data for Shot #1872.

comparison with the reported 75° bolometer data. After an anisotropy factor of 2 was taken into account, there was a large discrepancy between the two yields, much larger than was expected for the difference in acquisition time. After much discussion, it was hypothesized that the photocathode efficiencies of Channels 4, 5, and 7 were in actuality lower than had been previously assumed. A program to measure the photocathode quantum efficiencies and to determine the true response of XRD Channels 4, 5, and 7 was undertaken. In addition, the distances between the detectors and the source were remeasured.

A comparison of the measured quantum efficiencies, $\underline{Y_T}$, with those previously assumed is shown in Figure 45. The quantum efficiency for each channel was then extrapolated and interpolated to cover the entire detector energy range.

The distances from the detectors to the source were remeasured and the original distances were found to be incorrect. The distance to the source for Channels 1, 2, and 3 was found to be 152.4 cm and not 162.56 cm. The accompanying pinhole distance was found to be 83.185 cm from the source instead of 82.55 cm. The three high-energy channels were also found to be at 152.4 cm from the source and not 162.56 cm.

Figure 45. Measured and assumed quantum efficiencies for gold photocathodes of Channels 4, 5, and 7. Straight lines indicate presence of non-gold absorption edges.

Revised XRD responses were calculated by incorporating the new detector distances into the geometry and the measured photocathode efficiencies. The revised XRD response and the original response for Channels 4, 5 and 7 are compared in Figure 46.

These XRD responses with the addition of the geometrical factors corrected for the new distances will be referred to as the "post-calibrated" response of the XRD system. The originally assumed detector responses with the corrected geometrical factors will be referred to as the "original" response of the XRD system.

Bolometer and XRD Discrepancy

A series of pure neon gas shots was unfolded using one or both XRD responses. The resultant x-ray spectrum was then integrated over time and over the energy windows of the two bolometers in order for a direct comparison of the integrated yields to be made. The XRD yield was multiplied by an anisotropy factor of 2 to normalize the yield to that expected at 75° . These results are shown in Table 6. For low-yield data it is important to note that all the detectors had low signal-to-noise ratios and the discrepancy between the bolometer and XRD yields is greater.

Shots #1780, #1782, and #1783 were pure neon gas

Figure 46. Comparison of original and revised XRD response curves for Channels 4, 5, and 7.

TABLE 6. COMPARISON OF FOUR PURE NEON GAS SHOTS.

Shot Number	XRD Response	XRD		Bolometer		Bolo/ XRD Line Ratio	Bolo/ XRD Total Ratio	Comments
		Line Yield (kJ)	Total Yield (kJ)	Line Yield (kJ)	Total Yield (kJ)			
1780	Original	3.9	6.3	8.2	26.	2.1	4.1	11/84, Low Yield
1782	Original	17.6	32.1	13.6	37.	.77	1.2	11/84, XRD Channel 5 missing
1783	Original	8.0	13.4	11.4	29.	1.4	2.2	11/84, XRD Channel 1 missing
1855	Original	1.8	7.9	7.8	16.8	4.3	2.1	3/85, XRD Channel 1 missing
1855	Post- calibrated	5.4	8.7	7.8	16.8	1.4	1.9	3/85, XRD Channel 1 missing

shots that occurred toward the middle of the time-integrated run in the fall of 1984. Shot #1855 was the only pure neon gas shot of the time-resolved run that obtained usable XRD data. Shot #1782 had the highest yield and thus the highest signal-to-noise ratio. For this shot, the total and the line ratios of the bolometer-to-XRD data were of order one when the original XRD response was used for the unfold. This indicates that the original response was appropriate for shots that occurred early in the run.

Shot #1855 gave a better agreement between the bolometer and XRD yields when the post-calibrated response was used. Since all the good time-resolved multilayer data were obtained on shots after #1855, these shots were all unfolded using the post-calibrated XRD response.

The discrepancy between the yields of the bolometers and the XRD's increased significantly when neon was imploded upon a target, even though the post-calibrated response was used in the unfold. Table 7 summarizes these findings for 3 target shots. The discrepancies can be attributed to lower yields and varying amounts of obstruction in the line of sight of the XRD detectors caused by the target holder assemblies. This can be seen in the pinhole pictures taken at 75 degrees from the z -

TABLE 7. COMPARISON OF THREE NEON TARGET SHOTS.

Shot No.	Target	XRD				Bolometer				Bolo/ XRD Line Ratio	Bolo/ XRD Total Ratio
		Line		Total		Line		Total			
		Yield	FWHM	Yield	FWHM	Yield	FWHM	Yield	FWHM		
		(kJ)	(ns)	(kJ)	(ns)	(kJ)	(ns)	(kJ)	(ns)		
1860	V-doped foam	1.8	18	2.3	18	6.3	17	17.2	12	3.5	7.5
1872	V-doped foam	2.2	20	3.4	26	10.1	18	19.5	26	4.6	5.7
1875	Cu-Al- doped foam	3.5	22	4.5	25	9.6	22	26.7	27	2.7	5.9

axis, as shown in Figure 47.

Anisotropy

During an earlier run, an anisotropy was observed for pure neon gas shots that was on the order of 2 in the distribution of the total x-ray energy observed by bolometers at 13.5 and 60 degrees off the z-axis (Hanson, 1984). This reduction in the x-ray intensity near the axis was attributed partially to absorption by the presence of a cold column of gas above the imploding pinch. Maximum total x-ray yields were determined by multiplying the yields at 13.5 degrees by a factor of 2.

The practice of normalizing the near-axis bolometer yields to the off-axis bolometer by multiplying by 2 continued into the present runs, even though the off-axis bolometer had been changed to 75 degrees from 60 degrees. The geometry of the detector system used during the experimental runs is shown in Figure 48. This anisotropy factor was incorporated into the calculations of the XRD x-ray energy yields and has been included in the values reported in Table 7. However, from the pinhole picture shown in Figure 47, it would be expected that the anisotropy factor between the XRD's at 6.75 degrees and the bolometers at 75 degrees would be even greater than a factor of 2 for target shots.

Figure 47. X-ray pinhole photograph of Shot #1872 showing the target and the "spider web" target holder. The target holder blocks the x rays emitted from the plasma from reaching the diagnostics at angles closest to the $\underline{z}$ -axis.

Figure 48. Angular placement of x-ray diagnostics on PROTO II.

To further support the hypothesis of anisotropy, the relationship of the yields of two identical bolometers, one at 13.5 degrees and the other at 75 degrees, for target shots on the present run can be investigated. Table 8 summarizes the raw data containing no anisotropy factor. Table 8 indicates that a factor of two anisotropy is adequate for pure neon gas shots, but for target shots it can be a gross underestimate. The XRD-bolometer discrepancy does not seem unreasonable in the light of these numbers.

Similarity of Time History

Table 7 also shows the FWHM of the bolometer and XRD data. If the unfolded XRD spectrum is integrated only over the bolometer's energy window and plotted as a function of time, the curve traced out is very similar to that of the bolometer signal except that the scale is different. An example of this is shown in Figure 49, where the XRD data have been scaled appropriately for Shot #1872. The scaling factor has no anisotropy factor taken into account.

Conversion Efficiency

Since the bolometers and the XRD's were widely separated in yields, it was deemed prudent to determine whether the higher bolometer yields were in fact energet-

TABLE 8. COMPARISON OF YIELDS OF TWO IDENTICAL BOLOMETERS.

Shot Number	Target	Bolometer (kJ)		Anisotropy Factor
		^o 13.5	^o 75	
				^o 75 / 13.5 ^o
1855	None	8.7	16.8	1.9
1860	V-doped foam	6.4	17.2	2.7
1872	V-doped foam	5.8	19.5	3.4
1875	Cu-Al- doped foam	5.5	27.1	4.9

Figure 49. Comparison of line and total spectral power determined by XRD channels and bolometers for Shot #1872. XRD line signal scaled by 9.9 and the XRD total yield signal scaled by 8.0.

ically reasonable. This could be checked by calculating the kinetic energy available in the gas and comparing it with the bolometer total yield to determine a conversion efficiency.

A simple model calculation of the kinetic energy was done as follows. The magnetic pressure exerted onto the outside of a cylindrical shell of gas is assumed to be the only force acting upon the shell, and the pressure is acting upon the entire shell all at once. The shell and the variables to be used in the calculation are depicted in Figure 50. The force equation can be written as

$$\frac{md^2r_2}{dt^2} = \frac{B_{\theta}^2(t)A}{8\pi}, \quad (31)$$

where $A = 2\pi r_2 l$,

$m = \rho \text{Vol}_{\text{init}}$, and

$$B_{\theta} = \frac{2I(t)}{r_2 c}. \quad (32)$$

Here Vol_{init} is the initial shell volume, ρ is the neutral density of the plasma, c is the speed of light and $I(t)$ is the electrical current flowing into the pinch. By substituting Eq. (32) into Eq. (31), the acceleration of the shell, a , is obtained,

Figure 50. Imploding gas shell of inner radius r_1 , outer radius r_2 , and length, l , and cylindrical target of radius, r_f .

$$a(t) = \frac{d^2 r_2}{dt^2} = \frac{I^2(t)}{\frac{(\rho Vol_{init}) r_2(t) c^2}{\lambda}} \quad (33)$$

Adding the initial conditions of velocity and radius,

$$v(0)=0, \quad r_2(0) = r_{init},$$

the equations

$$v(t_j) = v(t_{j-1}) + a(t_{j-1})(t_j - t_{j-1}) \quad (34)$$

and

$$r_2(t_j) = r_2(t_{j-1}) + v(t_{j-1})(t_j - t_{j-1}) + 0.5a(t_{j-1})(t_j - t_{j-1})^2 \quad (35)$$

can be solved sequentially in time since the current as a function of time was measured by B detectors.

The last two conditions that determine the neutral density are the observed implosion time of the pinch and the final radius of the pinch, r_f . In the case of the gas imploding onto a target, the implosion time that is of interest is the time it takes the gas to implode upon the target, not the implosion of the gas-target system. The peak of the high-energy XRD channel is indicative of this implosion time. In accordance with this time, the final radius is the outer radius of the target. The neutral density is determined by iterating Eqs. (34) and (35) until the final radius is reached at the observed implosion time.

Once the density and the velocity at implosion is

determined, the kinetic energy can be calculated and compared with the bolometer yields. Figure 51 shows the input current and the calculated radius and velocity curves for Shot #1872, using a "best fit" neutral density of 6.5×10^{16} particles/cm³. This gives a kinetic energy of 65 kJ and a conversion efficiency of 30%. A conversion efficiency of 30% for this type of pulsed-power machine is reasonable.

Taking all these results into consideration, it was concluded that two incident spectra would be used in the calculation, essentially an upper and a lower value. The lower bound would be given by the unfolded x-ray spectrum, while the upper bound would be given by the unfolded XRD spectrum scaled such that the XRD spectrum integrated over energy matched the power as a function of time given by the 75° total bolometer.

Figure 51. Shot #1872 input current and calculated radius and velocity for a shell with $\rho = 6.5 \times 10^{16}$ particles per cubic centimeter.

CHAPTER II-5

HEATING MODEL

Once the incident spectral flux is known, the amount of energy absorbed in each layer as a function of time can be calculated. The energy deposition then allows the calculation of a variety of time-dependent thermophysical properties for each layer, such as temperature, expansion, and density. The reflection properties as a function of time can then be calculated according to the subsequent physical condition of the multilayer.

Energy Deposition

The first step in modeling the change in the multilayer's reflection properties when it is subjected to high energy x-ray flux is to determine how much energy is deposited in each layer during each time interval of the x-ray pulse. There are two ways to approach this. The first and the more straightforward way is to assume that each multilayer acts as an absorber of the incoming radiation. The second is to calculate the absorption according to matrix theory to include all contributions to the absorbed energy of both the forward- and backward-going components of the electromagnetic field

and not just the effective incident intensity.

In the first method, the calculated reflected spectrum of the whole multilayer is subtracted from the incident intensity, and this difference taken as the effective incident flux on the first layer. The effective incident flux is actually determined by taking one minus the reflectivity times the incident flux. The absorptance in the first layer, A_1 is as calculated from the equation

$$A_1 = (1 - t_1)(1 - R)i_o, \quad (36)$$

where i_o is the incident intensity, and

$$t_1 = \exp(-\mu_1 z_1 / \text{REAL}(\sin\theta_1)).$$

Here μ_1 is the linear absorption coefficient of the first layer, z_1 is the thickness of the first layer, and θ_1 is the grazing angle in the first layer. The resultant intensity incident on the second layer, i_2 , is given by

$$i_2 = (1 - R)t_1 i_o, \quad (37)$$

and so forth as shown in Figure 52. All the above quantities can be a function of energy.

In the second method, the ratio of the difference between the Poynting vector amplitudes at the two interfaces bracketing the layer of interest and the Poynting vector amplitude in the incident medium is calculated. This calculation follows Berning (1963).

FRACTION
AT INTERFACE

$$(1-R(E))i_0$$

$$(1-R)t_1 i_0$$

$$(1-R)t_1 t_2 i_0$$

$$(1-R)t_1 t_2 t_3 i_0$$

$$(1-R)t_1 t_2 t_3 t_4 i_0$$

⋮

$$I_j = (1-R)i_0 \prod_{m=1, j-1} t_m$$

FRACTION ABSORBED
IN LAYER

$$(1-R)(1-t_1)i_0$$

$$(1-R)t_1(1-t_2)i_0$$

$$(1-R)t_1 t_2 (1-t_3)i_0$$

$$(1-R)t_1 t_2 t_3 (1-t_4)i_0$$

⋮

$$A_j = (1-R)(1-t_j)i_0 \prod_{m=1, j-1} t_m$$

$$t_j = \exp(-\mu_j(E)z_j/\sin\theta_j(E))$$

Figure 52. Method for calculating absorptance, A_j , in layer j by assuming that the multilayer is an absorber subjected to an incident beam of intensity i_0 . The transmittance of layer j is given by t_j

Recalling the results from Chapter I-2, the matrix equation describing the multilayer is

$$\begin{bmatrix} E_o^{(t)} \\ E_o^{(r)} \end{bmatrix} = M \begin{bmatrix} E_{m+1}^{(t)} \\ E_{m+1}^{(r)} \end{bmatrix} . \quad (38)$$

This equation describes the incident, $E_o^{(t)}$, and reflected, $E_o^{(r)}$, electric field amplitudes in terms of the transmitted and reflected field amplitudes of the exit medium. Figures 8 and 9 of Chapter I-2 depict the labeling conventions used for the layers and interfaces. These electric field amplitudes are related to the total electric and magnetic field amplitudes inside each layer j by the relation

$$\begin{bmatrix} E_j \\ H_j \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \eta_j & -\eta_j \end{bmatrix} \begin{bmatrix} E_j^{(t)} \\ E_j^{(r)} \end{bmatrix} . \quad (39)$$

The matrix relation for relating the total electric and magnetic field amplitudes of one layer to the preceding layer is given by the equation

$$\begin{bmatrix} E_j \\ H_j \end{bmatrix} = \begin{bmatrix} \cos \varphi_j & -i/\eta_j \sin \varphi_j \\ -i\eta_j \sin \varphi_j & \cos \varphi_j \end{bmatrix} \begin{bmatrix} E_{j-1} \\ H_{j-1} \end{bmatrix} , \quad (40)$$

where η_j and φ_j are the effective index of refraction and phase thickness of layer j ; that is,

$\eta_j = n_j / \sin \theta_j$ for 'p' polarization, or

$\eta_j = n_j \sin \theta_j$ for 's' polarization,

and $\varphi_j = \frac{2\pi(n_j \sin \theta_j)}{\lambda}$.

Since the electric and magnetic field amplitudes are known, the effective Poynting vector amplitude,

$\text{REAL}[E_j H_j^*]$, at each interface can now be calculated.

The ratio of the difference between the two Poynting vector amplitudes at each interface surrounding the layer and the incident intensity on the upper side of the two interfaces is defined as the fractional absorptance, A_j , of that layer. In other words, A_j is expressed by the equation

$$A_j = \frac{4 \left(\text{REAL}[E_j H_j^*] - \text{REAL}[E_{j-1} H_{j-1}^*] \right)}{n_0 |E_0 + H_0|^2} \quad (41)$$

The equations (40) and (41) together give the recursion formula for the A_j 's. To get the energy deposited into the layer the A_j is multiplied by the incident spectral flux.

It is instructive to compare the results of the two methods. The R vs. E curve for a particular ϕ such as that given in Figure 53 has three distinct regions of interest the specular reflection region, the Bragg diffraction region, and that region which is far from the other two regions. Figures 54 through 56 compare the results for each method for the three regions for a 21-layer, tungsten-carbon multilayer of $2d=100 \text{ \AA}$, including the silicon substrate assuming s polarization. The absorptance is plotted as a histogram because no information of how the absorbed energy is distributed within the layer is calculated, only the total absorptance for that particular layer.

Figure 53. Reflectivity versus photon energy curve for a 21-layer, tungsten-carbon multilayer.

Figure 54. Absorptance calculated by the absorber and Poynting amplitude methods for the specular reflection region.

Figure 56. Absorptance calculated by the absorber and the Poynting amplitude method for the region far from the Bragg and specular reflection regions.

Figure 54 shows that in the specular reflection region more of the energy is absorbed in the first layer of tungsten by using the Poynting vector amplitude method than by using the absorber method. This is reasonable since in specular reflection there is a skin depth phenomenon (Henke, 1981a) not taken into account by the absorber method.

Figure 55 compares the two methods in the Bragg diffraction region. More absorption occurs in the top layers of tungsten in the absorber calculation than in the Poynting vector amplitude calculation.

Figure 56 shows the region far from the specular reflection region and far from the Bragg peak. It is encouraging to note that, as was expected, there is little difference, if any, between the two theories in this region.

Overall there is not a great difference between the results of the two methods. This is important since all of the experimental design calculations that were performed to determine the experimental parameters used the absorber method. However, the Poynting vector amplitude method was incorporated into the detailed modeling because of the large low-energy specular component of the spectral flux.

Thermophysical Properties

The enthalpy from room temperature for each layer, if conduction is ignored, is determined by integrating the deposited energy in the layer over the spectral range. By neglecting conduction, an upper limit for the heating can be obtained. Values of enthalpy as a function of temperature were taken from Hultgren et al. (1973a,b and c) for tungsten, carbon (graphite), and silicon. Enthalpy values through 4200° K for carbon, through 6000 °K for tungsten, and through 3600° K for silicon were used. The values for enthalpy were inverted to give temperature as a function of enthalpy. The inverted values were then fit with polynomials for different temperature regions, depending on the materials. This allowed for direct computation of the temperature at each layer.

With the temperature known at each time step, the corresponding expansion of the layers could be determined. Thermal expansion coefficients as a function of temperature were from Touloukian et al. (1975) for glassy carbon and silicon and Touloukian et al. (1970b) for tungsten. Expansion coefficients through 3600 °K for tungsten, through 2600 °K for carbon, and through 1600 °K for silicon were used. These were also fit with polynomials. The thermal expansion coefficient

polynomials were then used to calculate the change expected in the d -spacings of the layers in the multilayer.

The subsequent change in density of the layer due to the expansion was calculated by taking the original density, multiplying by the original thickness of the layer, and dividing by the expanded thickness. This assumes that the expansion occurred only in the z -direction. The density was required to calculate the index of refraction of the layer.

Multilayer Reflection Properties

To determine the reflectivity of the multilayer as a function of intensity and angle during the x-ray pulse, it would normally be necessary to partition the incident angle as well as time. However, from the discussion in Chapter II-3, the neon resonance lines were not distinct above the specular signal; therefore, the problem of modeling the temporal changes of the x-ray reflection properties reduces to a one-dimensional problem of the reflected flux integrated over energy at the central angle of incidence versus time.

To put this into practice, the R vs. E curve is calculated for each time step according to the calculated physical condition of the multilayer. A simplified flow

chart showing the logic of the code is shown in Figure 57. The reflected flux is determined by multiplying the R vs. E curve by the incident flux as a function of energy determined by the XRD-bolometer data. This reflected flux is then multiplied by the filter transmission and the fluorescer conversion efficiency as a function of energy and then integrated. This integrated response is then related to the density observed on the streak camera film. The computer program is given in Appendix B.

Figure 57. Simplified flow chart of the combined multilayer and heating computer code.

CHAPTER II-6

ANALYSIS

The two best shots from the time-resolved experiments were chosen to be examined closely. They were Shots #1863 and #1872.

Shot #1863

Out of the nine shots for which time-resolved data were obtained, Shot #1863 had the largest total yield. For Shot #1863 the tungsten-carbon multilayers used were set at an angle of 6.3° . OVLA-130-B-1-III was used in Spectrometer 1 and 0.5 of OVLA-130B-1-V was used in Spectrometer 2. Only $196.5 \mu\text{g}/\text{cm}^2$ Al postfilters were used on both spectrometers. Shot #1863 was also a pure neon shot and its spectral flux should be the easiest to determine; however, four of the six XRD's went off scale, preventing deconvolution of the spectrum. An attempt was made to determine whether the spectral shape of the incident flux as a function of time could be determined from other pure neon gas shots. The spectral flux of the four neon gas shots, #1780, #1782, #1783, and #1855, were deconvolved from their corresponding XRD data. These shots were previously tabulated in Table 6 of Chapter II-4. The resultant spectra were very dissimilar, making

it difficult to construct an incident spectrum to be used to model Shot #1863. This shot-to-shot variation can be seen in Figure 58, where the time-integrated data from the KAP spectrograph for three pure neon gas shots is shown. Detailed modeling was therefore not attempted.

Information on the destruction of the multilayer can be obtained by comparing the time history of the total yield bolometer data with the smoothed, compressed multilayer spectrometer data as shown in Figure 59. The left vertical axis is in terawatts (TW) radiated in 4π sr corresponding to the bolometer data, and the right vertical axis is erg/cm^2 deposited on the streak camera film. Zero time is arbitrary and set to the beginning of the streak of Spectrometer 1. The bolometer time was shifted such that the bolometer peak matched the peak of Spectrometer 1. Spectrometer 2 data were shifted with respect to Spectrometer 1 to account for the time of flight difference between the two. The averaging for the compressed streaks for the two spectrometer signals was over a different number of pixels. Spectrometer 2's signal was averaged over 4 times as many pixels as Spectrometer 1's, resulting in a lower average exposure. If Spectrometer 2's signal is scaled accordingly, as shown in Figure 60, it follows both the bolometer and Spectrometer 1 signals, dips a little, and then decays

Figure 58. Spectra taken with the KAP spectrograph fielded by M. A. Palmer for three neon gas shots showing the non-repeatability.

Figure 59. Total bolometer and multilayer spectrometer data for Shot #1863. The left-hand vertical axis is the total Power determined by the bolometer signal in 4π sr. The right-hand vertical axis is the exposure on the streak camera film.

Figure 60. Total bolometer and multilayer spectrometer data. Spectrometer 2 signal has been scaled to correspond to the other two signals.

rapidly at ~ 28 ns.

As can be seen in Figure 59, the control spectrometer signal, Spectrometer 1, has the same timing as the bolometer data. The streak camera data is noisy. Spectrometer 2's signal, once it gets out of the noise, decays on the rise of the two other signals. This indicates that the multilayer's reflectivity was decaying early, before the peak of the pulse. The power level determined from the bolometer at the start of the constant decay of the Spectrometer 2 data around ~ 28 ns is ~ 1.2 TW radiated in 4π sr. This is equivalent to 420 MW/cm² at the multilayer of Spectrometer 2.

The total integrated energy as a function of time that was produced can be determined by integrating the total yield bolometer signal. Figure 61 shows the integrated bolometer signal superimposed on the streak camera data. The total yield was 42.2 kJ into 4π sr, which is equivalent to a total dose of 15.0 J/cm² at the multilayer of Spectrometer 2. The decay of the multilayer reflection at 28 ns corresponds to ~ 14.9 kJ into 4π sr or a dose of 5.27 J/cm² at the multilayer of Spectrometer 2.

Shot #1872

Shot #1872 had good quality multilayer data as well

Figure 61. The integrated total bolometer signal and the data from the two multilayer spectrometers for Shot #1863. The left vertical axis gives the total integrated energy. The right axis gives the exposure on the streak camera film for the two compressed streaks.

as data from 5 out of the 6 XRD's. Channel 4 XRD failed. The multilayer used in Spectrometer 1 was OVLA 130B-1-III and the multilayer used in Spectrometer 2 was 0.5 of OVLA130B-1-IV, at an incidence angle of 6.26 degrees. Again only post filters were used and they were $123 \mu\text{g}/\text{cm}^2$ of Al for both spectrometers.

The total yield bolometer data and the smoothed compressed multilayer spectrometer data are shown in Figure 62. The left axis is the total power radiated by the plasma into 4π sr as detected by the bolometer. The right axis gives the averaged ergs/cm^2 on the streak camera film. Again Spectrometer 1's signal is a lot higher than Spectrometer 2's. This is again due to the averaging process and the background levels. Spectrometer 2 follows the other two signals, possibly dips, and then decays rapidly, indicating the degradation in the reflectivity of Spectrometer 2's multilayer. At the start of the continual decay at 19.5 ns the power level was $\sim 0.4 \text{ TW}$ into 4π sr or $141 \text{ MW}/\text{cm}^2$ at Spectrometer 2's multilayer.

The integrated energy of the bolometer as a function of time is superimposed on the multilayer data as shown in Figure 63. At 19.5 ns the plasma had produced an integrated energy of $\sim 5.5 \text{ kJ}$ into 4π sr which gives a dose of $2 \text{ J}/\text{cm}^2$. Since data for 5 out of the 6 XRD

Figure 62. Total bolometer and multilayer spectrometer data for Shot #1872. The left vertical axis is the total power in 4 π sr determined by the bolometer signal. The right vertical axis is the exposure on the streak camera film for the multilayer spectrometers.

Figure 63. The integrated total bolometer signal and the data from the two multilayer spectrometers for Shot #1872. The left vertical axis gives the total integrated energy, while the right vertical axis gives the exposure on the streak camera film for the two compressed streaks.

channels existed, detailed modeling was attempted.

The Spectrum as a function of time was deconvolved from the XRD data using the post-calibrated XRD responses and was shown in Figure 44. The difference between the total yields of the bolometers and XRD's was a factor of 9.4. However, as shown in Figure 48, the time history gives a scaling factor of 8.0. The scaling factor of 8.0 was used to determine the upper limit of heating, and a scaling factor of 1 would then correspond to the XRD yield.

The multilayer parameters were initialized such that carbon was on top, the tungsten d -spacing was 24.98 Å, and the carbon layers had d -spacings of 42.52 Å. The assumed initial densities were 19.3 g/cm³ for the tungsten layers and 2.0 g/cm³ for the carbon layers. The incidence angle was taken to be 6.25 degrees. The calculations were all done assuming unpolarized x rays.

With the assumption of no conduction the multilayer code calculated that the first tungsten layer (second layer in the stack) would be melted by the end of the x-ray pulse, for the multilayer in Spectrometer 1 at 150 cm from the source. As post-shot x-ray measurements showed, this multilayer was not destroyed, that is, melted, substantiating what was known all along, that is, that this model was unrealistic.

The calculations also showed that even up to near the melting temperature of the first tungsten layer, thermal expansion would not degrade the reflectivity over the spectral energy range of 25 eV to 3.2 keV more than 3 percent. However, thermal expansion would cause a shift of the Bragg diffraction peak as shown in Figure 64.

An average conduction factor can be determined by assuming that the melting of the first tungsten layer was the cause of the degradation in reflectivity. This assumption is not too unreasonable because at the melting of tungsten, carbon will diffuse into the tungsten very quickly. This can be seen in the following simplified discussion.

Fick's first law of diffusion (Askill, 1970) is given by

$$J = -D \frac{dc}{dx} \frac{\text{atoms}}{\text{cm}^2\text{-sec}}, \quad (42)$$

where J is the diffusion flux, D is the diffusion coefficient in units of cm^2/sec , and $\frac{dc}{dx}$ is the concentration gradient in atoms/cm^4 . The temperature-dependent diffusion coefficient can be expressed as

$$D = D_0 \exp(-Q/RT) \quad (43)$$

Here D_0 is the frequency factor in cm^2/sec (Askill, 1970), Q is the activation energy in cal/mole, R is the

Figure 64. Reflectivity curve around the Bragg diffraction peak for the initial multilayer parameters and for the expanded multilayer parameters at the melting temperature of the first tungsten layer for Shot #1872.

universal gas constant, and T is temperature in degrees kelvin. For carbon diffusing into tungsten, D_0 is $8.9 \times 10^{-3} \text{ cm}^2/\text{sec}$, and its activation energy is 53.5 kcal/mole in the temperature range of 1300–1900 °K (Askill, 1970). At higher temperatures these numbers could be slightly larger; however, these are adequate for the rough estimates. If the concentration of the carbon is taken to be that of the pure carbon layer and zero at the center of the tungsten layer ($dx = 12.5 \text{ Å}$), there is a concentration gradient of

$$\frac{dc}{dx} = 8.02 \times 10^{29} \text{ atoms/cm}^4,$$

assuming the density of the carbon layer is 2.0 g/cm^3 .

At the tungsten melting temperature, 3680° K the diffusion coefficient is given by

$$D = 5.76 \times 10^{-6} \frac{\text{cm}^2}{\text{sec}}.$$

Multiplying the concentration by the diffusion coefficient gives

$$J = 4.62 \times 10^{24} \frac{\text{atoms}}{\text{cm}^2\text{-sec}}.$$

The time it takes for one-half of a surrounding carbon layer (21.5 Å) to diffuse into the tungsten layer is t_d . This is determined by dividing the number of atoms per unit area in the half-carbon layer by the diffusion flux. In this case t_d is $2.13 \times 10^{16} \text{ atoms/cm}^2$. The diffusion time is therefore

$$t_D = \frac{N}{J} = \frac{2.13 \times 10^{16} \text{ atoms/cm}^2}{4.62 \times 10^{24} \text{ atoms/cm}^2\text{-sec}} = 4.6 \text{ ns.}$$

This gives a rough time for the destruction of the interfaces at the melting temperature of tungsten, assuming that the tungsten layer is still solid. If the tungsten layer turns liquid, diffusion may be very much faster. In addition, there may be other processes that occur when the tungsten layer melts that degrade the reflectivity very quickly.

Both Shot #1863 and Shot #1872 exhibited a small decay, then a "flat" signal level before a rapid decay began. For Shot #1872 the noise is such that this is hard to see but the dip is evident. By assuming that melting of the first tungsten layer began at the beginning of the "flat" signal, the temperature profiles of the first and second tungsten layers would look like that shown in Figure 65 superimposed on the signal of Spectrometer 2. Since the spectral power is increasing during this time, the reflectivity is really decreasing. The transition time from solid to liquid is of the same order as the "flat" signal and also the diffusion time calculated above. After the "flat" signal the reflectivity then decays rapidly as the temperature of the first tungsten layer rises rapidly, until a shorter "flat" signal is observed around 21 ns. The melting of the

Figure 65. Multilayer Spectrometer 2 streak camera data and the calculated temperature profile as a function of time for the two top tungsten layers. The right axis is exposure on the streak camera film for the two spectrometers. The left axis is the temperature of the layers.

second tungsten layer occurs at the end of this shorter "flat" signal. It would be expected that the second layer would reach melting faster than indicated, because it would receive heat from the upper layers. The melting of the second tungsten layer may then possibly correspond to the second shorter "flat" signal.

In order to match the timing of the beginning of the first tungsten layer's melting with the beginning of the first "flat" signal, the XRD spectral data were multiplied by a factor of 0.112. This indicates that conductivity reduced the heating of the multilayer by a factor of 10.2 for the low-yield limit. Using the more reliable bolometer yield would give an additional factor of 8, leading to a conductivity factor of 82. That is, because of heat conduction, the multilayer can withstand 82 times as much heat input before the top tungsten layer reaches melting temperature as it would for zero conductivity.

Discussion

Both sets of data from Shot #1863s and #1872 imply that the observed degradation of the multilayer reflectivity was a multi-step process. Since the multilayer was reflecting a large specular component compared with that from Bragg diffraction, the destruc-

tion of the multilayer reflectivity observed is indicative of a process occurring near the surface of the multilayer. The proposed mechanism of the carbon layers diffusing into the top tungsten layers and the melting of the tungsten layers is a surface process. It was calculated that differential thermal expansion of the multilayer could not explain the degradation seen. An average conductivity factor of 82 is not unreasonable.

These data indicate that tungsten-carbon multilayers are "two orders of magnitude more resilient to heat damage than "back of the envelope" calculations without conduction would indicate.

SUMMARY OF PART II

The experiments of the flash x-ray loading of metal multilayers were presented in Part II. Chapter II-1 discussed the x-ray source criteria and why PROTO II was chosen to be the x-ray source.

The time-integrated experiments were discussed and their results were presented in Chapter II-2. The time-integrated experiments laid the foundation for the time-resolved experiments discussed in Chapter II-3. Time-resolved data of the degradation of the multilayer reflectivity were obtained; however, a large specular component and poor spatial resolution prevented acquisition of distinct line profiles.

The methods used to determine the x-ray intensity emitted by the source, and thus incident on the multilayers, were discussed in Chapter II-4. The XRD gold photocathodes were post-calibrated and their measured responses were used to determine the spectral flux. Anisotropy factors were determined between the XRD data taken at 6.75 degrees from the z-axis, and bolometer data taken at 75 degrees from the z-axis.

Two different methods for calculating the absorptance of a layer in a multilayer were given in Chapter II-5. The first method was to calculate the difference

in the Poynting vectors at different sides of the multilayer, and the second was calculating the absorptance by assuming the multilayer was an absorber. The heating model presented in Chapter II-5 ignored conduction but included thermal expansion.

Time-resolved data from two shots were analyzed in Chapter II-6. For Shot #1863 two pieces of a tungsten-carbon multilayer with a $2d$ -spacing of $135 \text{ \AA}$ were used at 6.3 degrees. The Spectrometer 2 multilayer at 15 cm received a total dose of 15 J/cm^2 . The reflectivity of the multilayer of Spectrometer 2 decayed rapidly 28 ns from the beginning of the Spectrometer 1 streak camera trace. The corresponding power level at the multilayer was 420 MW/cm^2 , and the integrated dose was 5.27 J/cm^2 , as determined from the bolometer data.

For Shot #1872 two pieces of a tungsten-carbon multilayer with a $2d$ of $135 \text{ \AA}$ set at 6.25 degrees were used. The reflectivity of the Spectrometer 2 multilayer at 15 cm decayed rapidly at 19.5 ns after the start of the streak trace of Spectrometer 1. The corresponding power level and integrated dose determined from the bolometer data were 141 MW/cm^2 and 2 J/cm^2 , respectively.

For Shot #1872 detailed modeling was attempted. It was calculated that thermal expansion alone could not explain the degradation of the multilayer reflectivity

observed with Spectrometer 2. By matching the beginning of the first "flat" part of the signal observed by Spectrometer 2 with the start of melting of the first tungsten layer (second layer in the multilayer stack), conductivity factors of 10.2 and 82 for the amount of heat that could be absorbed before melting were determined from upper and lower estimates of the spectral flux. Since the bolometer data were taken at the same angle from the z -axis as the multilayer data, the factor of 82 was felt to be more reliable than the factor of 10.2 from XRD spectral data taken at an angle where obscuration of the line of sight could occur. This conductivity factor indicates that tungsten-carbon multilayers are nearly two orders of magnitude more resilient to heat damage than "back of the envelope" calculations without conduction would indicate.

FUTURE WORK

Because of the small incidence angles used in this investigation, the specular component reflecting from the multilayers and into the time-resolved detector system was so large that it washed out the line information, and thus the detailed information of the R versus θ curve that was desired. Such information, if obtained, would have been complicated by the finite and large size of the plasma source as seen by the multilayer 15 cm away. This experiment should be performed, if possible, with a smaller size source, and with larger incidence angles and better filtration to remove the specular component. This would give valuable information on the Bragg diffraction peaks with minimal background.

A further difficulty which was encountered that could be avoided was the determination of the x-ray spectral flux. Ideally one would like an infinite number of XRD's with narrow bandpasses over the spectral region of interest. If a similar experiment were to be run, it would be important to have the diagnostics that are to quantify the spectrum to be at the same angle from the plasma axis as the multilayers. This would eliminate the problem of anisotropy in the θ direction.

The fluorescer-fiber optic-streak camera system

could be made both more sensitive and to have better spatial and temporal resolution. It would help to shorten the fiber bundle by bringing the streak camera closer to the machine in its own EMP-shielded box. The fiber and the fluorescer could be changed such that the wavelength at which the fluorescer emits is more suited to being passed by the fiber optic.

If the improvements in the experimental design outlined above were done, information on how the multilayer's Bragg diffraction is degraded could be determined. It would also be valuable to investigate how the multilayer diffraction properties would change as the time scale of the x-ray heat loading was varied. This information would have direct application to the design and implementation of multilayer x-ray laser cavity mirrors, synchrotron monochromators, and multilayers used as high-temperature plasma diagnostics.

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APPENDIX A

MULTILAYERS AND COPPER L_{α} MEASUREMENTS

The multilayers were manufactured on three-inch-diameter silicon substrates and were cut in strips of 0.5-inch width for the heat loading experiments. The sectioning and labeling conventions followed are shown in Figure A1. Each disk had a name assigned by the manufacturer, and that label was kept for identification. The multilayers investigated and their general characteristics are given in Table A1.

Each multilayer section was measured at Cu L_{α} wavelength as described in Chapter I-1. The experimental results of these measurements are summarized in Table A2.

Figure A1. Sectioning and labeling used for three-inch multilayer disks.

TABLE A1. MULTILAYERS INVESTIGATED.

Name	Producer	Materials	Reported 2d-Spacing o (A)	Reported No. of Layers
a)				
83-021	Barbee	W/C	70	240
83-023A	Barbee	Mo/C	140	120
83-023B	Barbee	Mo/C	140	120
83-132(3)	Barbee	Mo/C	72	220
83-136(3)	Barbee	Pd/C	136	-
b)				
OVLA-070A-1	Ovonic	W/Si	72	200
OVLA-070A-2	Ovonic	W/Si	72	200
OVLA-070B-1	Ovonic	W/C	67	175
OVLA-070B-2	Ovonic	W/C	67	175
OVLA-130B-1	Ovonic	W/C	136	75

a) T. W. Barbee, Jr., Stanford University, presently at Lawrence Livermore National Laboratory.

b) Ovonic Synthetic Materials Company, Division of Energy Conversion Devices, Incorporated, Troy, Michigan.

TABLE A2. MEASURED MULTILAYER REFLECTION PROPERTIES AT
COPPER L_{α} WAVELENGTH.

Section	Percent Reflection	FWHM (mrad)	Integrated Reflectivity (mrad)	Effective 2d-spacing o (Å)
83-021				
I.	21.0	6.8	1.7	71.3
II.	22.0	6.5	1.7	71.9
III.	22.0	6.3	1.7	71.9
IV.	21.0	6.7	1.7	72.4
V.	21.0	6.8	1.7	72.3
83-023A				
I.	4.1	5.0	0.25	117.3
II.	4.8	4.0	0.24	115.9
III.	4.6	4.0	0.23	115.3
IV.	4.8	4.1	0.24	117.4
83-023B				
I.	5.3	4.3	2.8	118.4
II.	4.0	4.2	2.3	118.9
III.	4.6	4.0	2.3	119.6
IV.	4.6	3.7	2.2	117.6
V.	3.7	4.6	2.2	115.0

TABLE A2. Continued.

Section	Percent Reflection	FWHM (mrad)	Integrated Reflectivity (mrad)	Effective 2d-spacing o (Å)
83-132(3)				
I.	1.1	7.1	0.10	65.8
II.	2.7	4.4	0.14	66.5
III.	2.8	4.0	0.14	67.4
IV.	3.5	3.6	0.17	68.1
V.	2.7	4.2	0.14	68.4
83-136(3)				
I.	6.4	7.8	0.59	71.3
II.	6.3	7.7	0.58	71.8
III.	6.4	7.9	0.62	71.6
IV.	6.5	7.7	0.61	71.5
V.	6.5	7.9	0.61	72.1
OVLA-070A-1				
I.	22.0	5.5	1.2	72.4
II.	23.0	4.9	1.1	70.0
III.	27.0	4.2	1.5	68.6
IV.	25.0	4.2	0.9	69.1
V.	25.0	4.5	1.1	70.4

TABLE A2. CONTINUED

Section	Percent Reflection	FWHM (mrad)	Integrated Reflectivity (mrad)	Effective 2d-spacing o (Å)
OVLA-070A-2				
I.	22.0	5.2	1.4	73.1
II.	23.0	5.0	1.4	71.1
III.	26.0	4.3	1.4	69.1
IV.	26.0	4.3	1.4	69.5
V.	26.0	4.6	1.5	70.9
OVLA-070B-1				
I.	11.0	6.5	0.87	66.1
II.	15.0	5.3	1.1	68.6
III.	16.0	5.2	1.1	69.6
IV.	16.0	5.3	1.1	69.6
V.	14.0	5.8	1.0	68.5
OVLA-070B-2				
I.	13.0	6.9	1.0	64.6
II.	16.0	5.6	1.1	66.6
III.	17.0	5.2	1.2	67.8
IV.	17.0	5.2	1.1	68.2
V.	15.0	5.6	1.1	67.3

TABLE A2. CONTINUED

Section	Percent Reflection	FWHM (mrad)	Integrated Reflectivity (mrad)	Effective 2d-spacing o (Å)
OVLA-130B-1				
I.	25.0	8.2	2.3	107.6
II.	22.0	8.5	2.1	110.9
III.	25.0	8.3	2.3	112.0
IV.	26.0	8.7	2.2	112.2
V.	26.0	8.6	2.2	110.2

APPENDIX B. MULTILAYER COMPUTER CODE

```

=RCFT I=TIME
=LDR B=(BMSPEXP,BCSPEXP).X=XSPEXP,LIB=(CFTLIB.D:SCFT)

PROGRAM XRAY (SCATFACX,VALUESX,TTY,TAPE6=TTY,

1  TAPE3=SCATFACX,TAPE4=VALUESX,TEMP,REFL,DSpace,
2  SPECTRUM,TAPE2=SPECTRUM,ENTH,TAPE7=TEMP,TAPE8=REFL,
3  RTINT,TAPE1=RTINT,TABLES,TAPE5=TABLES,TIME,
4  TAPE9=TIME,TAPE9=DSpace,TAPE10=ENTH,HRATE,
5  TAPE11=HRATE,DE,TAPE12=DE,DEINT,TAPE13=DEINT)

PARAMETER (LAY=60)

IMPLICIT COMPLEX (C)
DIMENSION RRINT(60)
COMMON ASCAT(LAY,100),BSCAT(LAY,100),ISTRUC(4,2,LAY)
COMMON DENS(LAY),CPSI(LAY,100),Z(LAY),E(100),CP(LAY,100)
COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RINDO,CI,CPSIC
COMMON /RTD/ R(100),THRU(100),DEINT(LAY),DESUM(LAY),TEMP(LAY),DT
COMMON /TIME/NTIME,TIMES(60),ASORCE,DLSM,DEET,ITSAVE

TIME=0.
CALL BLKDAT
CALL RTIME

C
C SET UP INITIAL MULTILAYER STRUCTURE
C
CALL OPT1(NLAYER,NPERIOD,NE,ANG)

C
C READ ENERGY ARRAY
C
CALL RDENGY(E,NE)
ITSAVE=1
DO 100 I=1,NTIME
TIME=TIME
TIME=TIMES(I)
DT=TIME-TIME1
CALL LSM(ANG,RINT,TIME,RRINT(I),NE,NLAYER,NPERIOD)
100 CONTINUE

C
C PRINT OUT THE INTEGRATED ENERGY THE FLUOR PRODUCES AS
C A FUNCTION OF TIME
C
C-- WRITE(1,1929)
1929 FORMAT(' INTEGRATED ENERGY THE FLUOR PRODUCES')
C-- WRITE(1,1930)(TIMES(I),I=1,NTIME)
C-- WRITE(1,1930)(RRINT(I),I=1,NTIME)
1930 FORMAT(1P6E12.4)
C
END
SUBROUTINE LSM(ANG,RINT,TIME,RRINT,NE,NLAYER,NPERIOD)
C
C THIS SUBROUTINE IS THE MAIN DRIVER FOR THE LSM CALCULATIONS
C
PARAMETER(LAY=60)
IMPLICIT COMPLEX (C)
C
COMMON ASCAT(LAY,100),BSCAT(LAY,100),ISTRUC(4,2,LAY)
COMMON DENS(LAY),CPSI(LAY,100),Z(LAY),E(100),CP(LAY,100)
COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RINDO,CI,CPSIC
COMMON /RTD/ R(100),THRU(100),DEINT(LAY),DESUM(LAY),TEMP(LAY),DT

C
C SET UP INCIDENT SPECTRUM FOR TIME TIME
C
CALL SPECTRM(TIME,NE,E)
C
C CALCULATE REFLECTIVITY AND ABSORPTANCE
C
CALL OPT4(NLAYER,NPERIOD,NE,ANG,RINT,RRINT)
RETURN
END

C
SUBROUTINE PERIOD0(NPERIOD,CHMAT,NE,NLAYER)
C
C THIS SUBROUTINE SETS UP CALCULATIONS FOR INITIAL PERIOD
C
C VARIABLES

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C
C ISTRUC(1,1,NLAYER-1) --- ATOMIC SYMBOL OF THE 1ST ELEMENT OF EXIT MEDIUM
C
      PARAMETER (LAY=60)
      IMPLICIT COMPLEX (C)
      DIMENSION CHMAT(2,2,100)
      COMMON ASCAT(LAY,100),BSCAT(LAY,100),ISTRUC(4,2,LAY)
      COMMON DENS(LAY),CPSI(LAY,100),Z(LAY),E(100),CP(LAY,100)
      COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RINDO,CI,CPSIO

C
C      ISTRUC(1,1,NLAYER-1)=0
C
C      SETUP THE ATOMIC FORM FACTOR ARRAYS FOR FOLLOWING CALCULATIONS
C
C      CALL FSCAT(ASCAT,BSCAT,ISTRUC,DENS,NLAYER,E,NE)
C
C      CALCULATE THE NEEDED PARAMETERS
C
C      CALL LAYER(CHMAT,NE,NLAYER)
C      RETURN
C      END
C      SUBROUTINE COMBINE(CHMAT,NE,NLAYER)

C
C      THIS SUBROUTINE COMBINES THE CHARACTERISTIC MATRIX FOR N=1
C      TO NLAYER WITH THE FINAL MATRIX TAKING INTO ACCOUNT THE
C      EXIT MEDIUM, AND CALCULATES THE RESULTANT R(IE)
C
C      VARIABLES
C
C      CMATRX --- CHARACTERISTIC MATRIX FOR NLAYER LSM
C      CPO --- SINE OF THE INITIAL ANGLE
C      CP(N,IE) --- SINE OF ANGLE FOR LAYER N TIMES THE INDEX OF REFRACTION
C                  OF LAYER N FOR ENERGY E(IE)
C      R(IE) --- UNIT REFLECTIVITY AT ENERGY E(IE)
C      T(IE) --- UNIT TRANSMISSION AT ENERGY E(IE)
C      D(IE) --- UNIT ABSORPTION FOR WHOLE LSM AT ENERGY E(IE)
C
      PARAMETER (LAY=60)
      IMPLICIT COMPLEX (C)
      DIMENSION R(100),T(100),D(100),THRU(100)
      COMMON ASCAT(LAY,100),BSCAT(LAY,100),ISTRUC(4,2,LAY)
      COMMON DENS(LAY),CPSI(LAY,100),Z(LAY),E(100),CP(LAY,100)
      DIMENSION CHMAT(2,2,100)
      COMMON /RTD/ R,THRU,D,INT(LAY)

      NN=NE
      DO 200 IE=1,NN

          CPO=CSIN(CPSI(1,IE))
          CR1=.5*(CP(NLAYER,IE)+CP(NLAYER+1,IE))/CP(NLAYER,IE)
          CR2=.5*(CP(NLAYER,IE)-CP(NLAYER+1,IE))/CP(NLAYER,IE)
          CTT=CHMAT(1,1,IE)=CR1+CHMAT(1,2,IE)=CR2
          CRR=(CHMAT(2,1,IE)=CR1+CHMAT(2,2,IE)=CR2)/CTT
          CHMAT(1,2,IE)=CR2+CHMAT(1,1,IE)+CR1=CHMAT(1,2,IE)
          CHMAT(2,2,IE)=CR2+CHMAT(2,1,IE)+CR1=CHMAT(2,2,IE)
          CHMAT(1,1,IE)=CTT
          CHMAT(2,1,IE)=CRR-CTT
          CTT=1./CTT
          R(IE)=REAL(CRR)=REAL(CRR)+AIMAG(CRR)=AIMAG(CRR)
          T(IE)=REAL(CTT)=REAL(CTT)+AIMAG(CTT)=AIMAG(CTT)
          D(IE)=1.-R(IE)-T(IE)
      200 CONTINUE
      RETURN
      END
      SUBROUTINE LAYER (CHMAT,NE,NLAYER)

C
C      THIS SUBROUTINE SETS UP THE ANGLES AND THE CHARACTERISTIC
C      MATRIX
C
C      VARIABLES
C
C      ASCAT(N,I) --- DELTA,REAL PART OF THE INDEX OF REFRACTION FOR
C                  LAYER N AT ENERGY E(I)
C      BSCAT(N,I) --- BETA,IMAGINARY PART OF THE INDEX OF REFRACTION FOR
C                  LAYER N AT ENERGY E(I)
C      CI --- SORT OF -1
C      CMATRX --- CHARACTERISTIC MATRIX

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C CN(N)      --- COMPLEX INDEX OF REFRACTION OF LAYER N
C CNO        --- COMPLEX INDEX OF REFRACTION OF INITIAL MEDIUM
C CP(N,I)    --- SINE THETA OF LAYER N TIMES THE INDEX OF REFRACTION OF LAYER N
C CPSI(N+1,I) --- ANGLE OF LAYER N FOR ENERGY E(I)
C WAVELEN    --- WAVELENGTH CORRESPONDING TO GIVEN ENERGY
C
  PARAMETER (LAY=60)
  IMPLICIT COMPLEX (C)
  COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RINDO,CI,CPSIO
  COMMON /POLAR/ FP
  COMMON ASCAT(LAY,100),BSCAT(LAY,100),ISTRUC(4,2,LAY)
  COMMON DENS(LAY),CPSI(LAY,100),Z(LAY),E(100),CP(LAY,100)
  DIMENSION CPHI(LAY),CN(LAY)
  DIMENSION CHMAT(2,2,100)
C
  DO 200 I=1,NE
    WAVELEN=EVCM/E(I)

C
C   CALCULATE INDEX OF REFRACTION FOR EACH LAYER
C
    NL1=Nlayer+1
    DO 100 N=1,Nlayer
      CN(N)=CSORT(1,-ASCAT(N,I)-CI-BSCAT(N,I))
      CN(NL1)=(1.0,0.0)
      CNO=RINDO
100
C
C   CALCULATE APPROPRIATE COMPLEX ANGLE FOR EACH LAYER
C
    CALL SNELL(CP(1,I),CPSI(1,I),ASCAT(1,I),BSCAT(1,I),CPHI,
C    CN,CNO,Nlayer)
C
C   CALCULATE THE CHARACTERISTIC MATRIX FOR EACH ENERGY E(I)
C
    IE=I
    CALL CMATRX(CPHI,CPSI(1,I),CN,Z,CHMAT(1,1,I),WAVELEN,
C    Nlayer,FP,CNO)
200 CONTINUE

    RETURN
  END
  SUBROUTINE CMATRX (CPHI,CPSI,CN,Z,CHMAT,WAVELEN,
1 Nlayer,FP,CNO)
C
C   THIS SUBROUTINE CALCULATES THE CHARACTERISTIC MATRIX
C   FOR EACH LAYER N, AND THEN MULTIPLIES THE CHARACTERISTIC
C   MATRICES TOGETHER TO GET THE CHARACTERISTIC MATRIX
C   FOR THE ENTIRE MULTILAYER
C
C   VARIABLES
C
C   CA - SINE OF ANGLE A
C   CB - SINE OF ANGLE B
C   CFACT - "EFFECTIVE" PHASE THICKNESS
C   CFRES - FRESNEL COEFFICIENT BETWEEN MEDIUM OF INCIDENT
C           ANGLE A AND MEDIUM OF EXIT ANGLE B
C   CFRESI - FRESNEL COEFFICIENT FOR CHARACTERISTIC MATRIX
C   CNO - INDEX OF REFRACTION OF INITIAL MEDIUM
C   CN(N) - INDEX OF REFRACTION OF LAYER N
C   CPSI(N+1) - COMPLEX ANGLE INSIDE LAYER N
C   CPHI(N) - SIN OF THE COMPLEX ANGLE IN LAYER N
C   FP =1. - "S" POLARIZATION
C   FP =2. - "P" POLARIZATION
C   WAVELEN - WAVELENGTH AT WHICH THE MATRIX IS TO BE CALCULATED
C   Z(N) - PHYSICAL THICKNESS OF LAYER N
C   PARAMETER (LAY=60,
C   IMPLICIT COMPLEX (C)
C   DIMENSION CHMAT(2,2),CHMAT1(2,2),CPHI(1),CPSI(1),CN(1)
C   DIMENSION Z(1)
C   COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RINDO,CI,CPSIO
C
C   CALCULATE MULTILAYER CHARACTERISTIC MATRIX
C
    PI2=2.*PI

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CFACT=PI2/WAVELEN=CPHI(1)=Z(1)
CA=CSIN(CPSI(1))
CB=CSIN(CPSI(2))
IF(FP.EQ.1) THEN
  CFRES=(CNO-CA-CN(1)=CB)/(CN(1)=CB+CNO-CA)
ELSE
  CFRES=(CNO-CB-CN(1)=CA)/(CN(1)=CA+CNO-CB)
ENDIF
CFRESI=1./(1.+CFRES)

C
C INITIALIZE CMATRX TO CHARACTERISTIC MATRIX OF LAYER 1
C

CHMAT(1,1)=CFRESI=CEXP(CI-CFACT)
CHMAT(2,1)=CFRESI-CFRES=CEXP(CI-CFACT)
CHMAT(1,2)=CFRESI-CFRES=CEXP(-CI-CFACT)
CHMAT(2,2)=CFRESI=CEXP(-CI-CFACT)

C
IF(NLAYER.EQ.1) RETURN
DO 100 N=2,NLAYER
  CFACT=PI2/WAVELEN=CPHI(N)=Z(N)
  CA=CSIN(CPSI(N))
  CB=CSIN(CPSI(N+1))

C
  IF(FP.EQ.1) THEN
    CFRES=(CN(N-1)=CA-CN(N)=CB)/(CN(N)=CB+CN(N-1)=CA)
  ELSE
    CFRES=(CN(N-1)=CB-CN(N)=CA)/(CN(N)=CA+CN(N-1)=CB)
  ENDIF
  CFRESI=1./(1.+CFRES)

  CHMAT1(1,1)=CFRESI=CEXP(CI-CFACT)
  CHMAT1(2,1)=CFRESI-CFRES=CEXP(CI-CFACT)
  CHMAT1(1,2)=CFRESI-CFRES=CEXP(-CI-CFACT)
  CHMAT1(2,2)=CFRESI=CEXP(-CI-CFACT)

C
C MULTIPLY MATRIX WITH PREVIOUS PRODUCT
C
  CALL MMULT(CHMAT,CHMAT1)

C
100 CONTINUE
  RETURN
END
SUBROUTINE MMULT(CHMAT,CHMAT1)
  PARAMETER (LAY=60)
  COMPLEX CHMAT(2,2),CHMAT1(2,2),CSUM(2,2)

C
C COMPLEX MATRIX MULTIPLY CHMAT1 BY CHMAT FROM THE LEFT AND
C RETURNS PRODUCT INTO CHMAT

  DO 100 I=1,2
    DO 100 J=1,2
      CSUM(I,J)=(0.,0.)
      DO 50 K=1,2
        CSUM(I,J)=CSUM(I,J)+CHMAT(I,K)*CHMAT1(K,J)
      50 CONTINUE
    100 CONTINUE
    DO 200 I=1,2
      DO 200 J=1,2
        200 CHMAT(I,J)=CSUM(I,J)
      RETURN
    END
  SUBROUTINE INIMAT(CHMAT)

C
C INITIALIZES MATRIX CHMAT(2,2,K) TO 2X2 IDENTITY MATRIX FOR K=1,100
C

  PARAMETER (LAY=60)
  COMPLEX CHMAT(2,2,100)
  DO 100 I=1,100
    CHMAT(1,1,I)=1.
    CHMAT(2,2,I)=1.
    CHMAT(1,2,I)=0.
  100 CHMAT(2,1,I)=0.
  RETURN
END
SUBROUTINE SNELL (CP,CPSI,ASCAT,BSCAT,CPHI,CN,CNO,NLAYER)
  PARAMETER (LAY=60)
  IMPLICIT COMPLEX (C)
  DIMENSION CP(1),CPSI(1),CPHI(1),CN(1),ASCAT(1),BSCAT(1)
  COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RINDO,CI,CPSIO

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```

C      THIS SUBROUTINE CALCULATES THE COMPLEX ANGLE IN LAYER N
C      ACCORDING TO THE COMPLEX SNELL'S LAW
C
C  VARIABLES
C
C  CCPSI --- ANGLE IN THE PARTICULAR LAYER
C  CNN --- RATIO OF THE PARTICULAR INDEX OVER THE INITIAL INDEX
C  CNO --- INITIAL INDEX OF REFRACTION
C  CP(N) --- THE PRODUCT OF THE INDEX OF REFRACTION AND THE SINE OF
C           THE ANGLE OF LAYER N
C  CPHI(N) --- CP(N) EXCEPT FOR N=Nlayer+1 WHEN IT IS EQUAL TO 1./CP
C  CPS --- COSINE OF THE INCIDENT ANGLE
C  CPSI --- SQUARE OF THE COSINE OF THE INCIDENT ANGLE
C  CPSI(N+1) --- COMPLEX ANGLE IN THE N+1TH LAYER
C  Nlayer --- NUMBER OF LAYERS INCLUDING THE SUBSTRATE
C  CNL1 --- Nlayer + 1
C
      IF(CPSIO.EQ.(0.,0.)) CPSI=CSIN(CPSI(1))
      CPS=CCOS(CPSI(1))
      CPS2=CPS-CPS
      NL1=Nlayer+1
      DO 100 N=1,NL1
        CNN=CN(N)/CNO
        CCPSI=CSORT(CNN-CNN-CPS2'/CNN)
100    CPSI(N+1)=CASIN(CCPSI)
      DO 150 N=1,Nlayer
        CPS=CSIN(CPSI(N+1))
        CPHI(N)=CPS-CN(N)
150    CP(N)=CPS-CN(N)
      CPS=CSIN(CPSI(NL1+1))
      CPHI(NL1)=1./CPS
      CP(NL1)=CPS
      RETURN
      END
      SUBROUTINE BLKDAT
C
C  THIS SUBROUTINE SETS THE VALUES OF CONSTANTS TO BE USED
C
      PARAMETER (LAY=60)
      IMPLICIT COMPLEX (C)
      COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RINDO,CI,CPSIO
      DATA PI/3.14159265/,RO/2.917938E-13/,AMU/1.66055E-24/
      DATA ANGEV/12398.54/,EVCM/12398.54E-3/
C
C  AMU --- ATOMIC MASS UNIT (GRAMS)
C  ANGEV --- CONVERSION FACTOR FROM EV TO ANGSTROMS
C  CI --- SQUARE ROOT OF -1
C  CPSIO --- INITIAL ANGLE
C  EVCM --- CONVERSION FACTOR FROM EV TO CM
C  PI --- 3.14159265
C  RAD --- RADIAN-DEGREE CONVERSION FACTOR
C  RINDO --- INDEX OF REFRACTION OF VACUUM
C  RO --- CLASSICAL ELECTRON RADIUS
C
      RAD=PI/180.
      RINDO=1.
      CI=(0.,1.)
      CPSIO=0.
      RETURN
      END
      SUBROUTINE F1F2(Z,OUTFIL,ATWT,RMU,EMF,NAME)
C
C  THIS SUBROUTINE READS IN THE ATOMIC SCATTERING FACTORS
C  F1 AND F2
C
      PARAMETER (LAY=60)
      COMMON /ENLOG/ ENERGY(400),MAX
      DIMENSION OUTFIL(400,2)
      INTEGER Z,ZO
      IF (Z.GE. 1) GO TO 10
      ATWT=-1.0
      RETURN
10  IADDR=(Z-1)*1201
      CALL RDISK(3,MAX,1,IADDR)
      IF(UNIT(3))11,100,110
11  IADDR=IADDR+1
      CALL RDISK(3,ENERGY,400,IADDR)
      IF(UNIT(3))12,100,110
12  IADDR=IADDR+400

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      CALL RDISK(2,OUTFIL,800,1ADDR)
      IF(UNIT(3))13,100,110
13  REWIND 4
      DD 20 I=1,2
          READ (4,15) ZO,NAME,ATWT,RMU,EMF
15      FORMAT (12,1X,A2,3E12.5)
20  CONTINUE
      RETURN
100 WRITE(6,1000)
1000 FORMAT(' EOF ON FILE SCATFACT')
      RETURN
110 WRITE(6,1001)
1001 FORMAT(' I/O ERROR ON FILE SCATFACT')
      RETURN
      END
      SUBROUTINE FSCAT (ASCAT,BSCAT,ISTRUC,DENS,NLAYER,E,NE)
C
C   THIS SUBROUTINE TAKES THE ATOMIC SCATTERING FACTORS F1 AND F2
C   AND CALCULATES THE REAL AND IMAGINARY PARTS OF THE INDEX OF
C   REFRACTION OF LAYER N ACCORDING TO
C   B.L. HENKE ET.AL. ,ATOMIC AND NUCLEAR DATA TABLES, VOL. 27,P1-144(1982)
C
C   VARIABLES
C
C   ASCAT(N,IE) --- DELTA, REAL PART OF THE INDEX OF REFRACTION
C   ATWT --- ATOMIC WEIGHT OF THE HEAVY ELEMENT
C   ATWTL --- ATOMIC WEIGHT OF THE LIGHT ELEMENT
C   ATWTS --- ATOMIC WEIGHT OF THE SUBSTRATE
C   BSCAT(N,IE) --- BETA, IMAGINARY PART OF THE INDEX OF REFRACTION
C   DENSIN) --- THE DENSITY OF THE N'TH LAYER
C   IEL --- ATOMIC SYMBOL FOR THE I'TH ELEMENT IN THE N'TH LAYER
C   ISTRUCT(I,1,N)--- THE ATOMIC NUMBER OF THE I'TH ELEMENT OF THE N'TH LAYER
C   ISTRUCT(I,2,N) --- NUMBER OF ATOMS OF THE I'TH ELEMENT IN THE N'TH LAYER
C   F1SUM --- WEIGHTED SUM OF F1
C   F2SUM --- WEIGHTED SUM OF F2
C   NLAYER --- THE NUMBER OF LAYERS INCLUDING THE SUBSTRATE
C   WAVELEN --- WAVELENGTH OF PARTICULAR ENERGY E
      PARAMETER (LAY=60)
      COMPLEX CI,CPSIO
      COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RINDO,CI,CPSIO
      COMMON /ENLGG/ ENERGY(400),MAX
      COMMON /F1F2/IH,IL,F1F2H(400,2),F1F2L(400,2),
      - F1F2S(400,2),IS,ATWTH,ATWTL,ATWTS,EMFH,EMFL,EMFS
      COMMON /EN/MAXH,MAXL,MAXS,EL(400),ES(400),EH(400)
      DIMENSION ISTRUC(4,2,LAY),DENS(LAY),E(100)
      DIMENSION ASCAT(LAY,100),BSCAT(LAY,100)
      DIMENSION OUTFIL(400,2),F1SUM(100),F2SUM(100)
C
C   INITIALIZE SUMMATION VARI
C
      NL1=NLAYER+1
      DO 200 N=1,NL1
        DO 90 IE=1,NE
          F1SUM(IE)=0.
          F2SUM(IE)=0.
        90 CONTINUE
        WSUM=0.
C
C   COMPUTE THE AVERAGE ATOMIC SCATTERING FACTOR FOR EACH LAYER BY
C   FINDING THE WEIGHTED SUM FOR ALL ELEMENTS IN EACH LAYER
C
      DO 100 I=1,4
        IEL=ISTRUC(I,1,N)
        IF(IELEQ.IH)THEN
          CALL SWITCH(OUTFIL,F1F2H)
          CALL SWITCHE(ENERGY,MAX,EH,MAXH)
          ATWT=ATWTH
        ENDIF
        IF(IELEQ.IL)THEN
          CALL SWITCH(OUTFIL,F1F2L)
          CALL SWITCHE(ENERGY,MAX,EL,MAXL)
          ATWT=ATWTL
        ENDIF
        IF(IELEQ.IS)THEN
          CALL SWITCH(OUTFIL,F1F2S)
          CALL SWITCHE(ENERGY,MAX,ES,MAXS)
          ATWT=ATWTS
        ENDIF
        IF(ISTRUC(I,1,N).EQ.0)ATWT=-1
        IF(ATWT.LT.0.) GOTO 150

```

```

      DO 95 IE=1,NE
      F1SUM(IE)=F1SUM(IE)+EINTRP(E(IE),OUTFIL)-ISTRUC(I,2,N)
      F2SUM(IE)=F2SUM(IE)+EINTRP(E(IE),OUTFIL+1,2)-ISTRUC(I,2,N)
95    CONTINUE
      WSUM=WSUM+ISTRUC(I,2,N)*ATWT*AMU
100   CONTINUE
C
C   FOR EACH ENERGY POINT CALCULATE THE REAL AND IMAGINARY PARTS OF THE
C   INDEX OF REFRACTION
C
      DO 180 IE=1,NE
      WAVELEN=EVCN/E(IE)
      WAV2=WAVELEN*WAVELEN
      IF(ISTRUC(1,1,N).EQ.0) THEN
        ASCAT(N,IE)=C.
        BSCAT(N,IE)=C.
      ELSE
        FACT=RO/PI*WAV2*OENS(N)/WSUM
        ASCAT(N,IE)=FACT*F1SUM(IE)
        BSCAT(N,IE)=FACT*F2SUM(IE)
      ENDIF
180   CONTINUE
200   CONTINUE
300   CONTINUE
      RETURN
      END
      FUNCTION EINTRP (EN,Y)
C
C   THIS SUBROUTINE INTERPOLATES ENERGY VALUES TO LOOK UP IN
C   DATA TABLES.
C
      COMMON /ENLOG/ ENERGY(400),MAX
      DIMENSION Y(400)
      DO 100 I=1,MAX
      IF(EN.LT.ENERGY(I)) GOTO 150
100   CONTINUE
      I=MAX
120   EINTRP=Y(I)
      RETURN
150   IF (I.EQ.1) GOTO 120
      EN2=ALOG(ENERGY(I))
      EN1=ALOG(ENERGY(I-1))
      EINTRP=(ALOG(EN)-EN1)/(EN2-EN1)*(Y(I)-Y(I-1))+Y(I-1)
      RETURN
      END
      SUBROUTINE MAXX(E,NE,XMAX)
C
C   DETERMINES THE MAX BETWEEN XMAX AND E(I)
C
      PARAMETER (LAY=60)
      DIMENSION E(NE)
      DO I=1,NE
10    IF (E(I).GT.XMAX) XMAX=E(I)
      RETURN
      END
      SUBROUTINE DELTAE(CHMAT,NE,DE,NLAYER)
C
C   THIS SUBROUTINE CALCULATES THE ABSORPTANCE FOR EACH LAYER J
C   FOR EACH ANGLE OR ENERGY POINT I . ACCORDING TO
C   P.H. BERNING, "THEORY AND CALCULATIONS OF OPTICAL THIN FILMS",
C   PHYSICS OF THIN FILMS,VOL. 1,P69-121(1963)
C
      CAPPHI(J) - "EFFECTIVE" PHASE THICKNESS OF LAYER J
      CNIN) - COMPLEX INDEX OF REFRACTION OF LAYER N
      CNN(N) - "EFFECTIVE" INDEX OF REFRACTION
      CPSI(N+1)- COMPLEX ANGLE OF LAYER N
      CEZERO - INCIDENT MEDIUM ELECTRIC FIELD AMPLITUDE
      CHZERO - INCIDENT MEDIUM MAGNETIC FIELD AMPLITUDE
      DE(J,I)- ABSORPTANCE IN LAYER J FOR I'TH POINT ACCORDING TO
C   MATRIX THEORY
      DENS(J) - DENSITY OF LAYER J
      NE - NUMBER OF POINTS
      NLAYER - NUMBER OF LAYERS INCLUDING THE SUBSTRATE
      POYNTJ - POYNTING VECTOR AMPLITUDE IN THE J'TH LAYER
      POYNTJM - POYNTING VECTOR AMPLITUDE IN THE J-1'TH LAYER
      R(I) - UNIT REFLECTIVITY OF POINT I
      RINDO = INDEX OF REFRACTION IN THE INCIDENT MEDIUM

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C      RRINDO - "EFFECTIVE" INDEX OF REFRACTION IN THE INCIDENT MEDIUM
C      RMU - MASS ABSORPTION COEF FOR LAYER J
C      TRANS - TRANSMISSION THROUGH LAYER J
C      Z(J) - PHYSICAL THICKNESS OF LAYER J
C
C      PARAMETER(LAY=60)
C      IMPLICIT COMPLEX (C)
C      DIMENSION CHMAT(2,2,100),CHMATO(2,2),DE(LAY,100),DEA(LAY,100)
C      DIMENSION CHMAT1(2,2),CN(LAY),OUTFIL(400,2),THRUU(100)
C      DIMENSION R(100),THRU(100),CNN(LAY)
C      COMMON /RTD/R,THRU,DEINT(LAY)
C      COMMON ASCAT(LAY,100),BSCAT(LAY,100),ISTRUC(4,2,LAY)
C      COMMON DENS(LAY),CPSI(LAY,100),Z(LAY),E(100),CP(LAY,100)
C      COMMON /ENLOG/ENERGY(400),MAX
C      COMMON /POLAR/FP
C
C      COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RRINDO,CI,CPSIO
C      NN=NE
C      DO 50 II=1,NN
C          THRUU(II)=1.-R(II)
50  CONTINUE
C      DC 200 I=1,NN
C
C      CALCULATE THE INDEX OF REFRACTION
C
C      NL1=Nlayer+1
C      DO 75 N=1,Nlayer
C          CN(N)=CSQRT(1.-ASCAT(N,I)-CI*BSCAT(N,I))
C
C      CALCULATE THE "EFFECTIVE" INDEX OF REFRACTION
C
C          IF(FP.EQ.1.)CNN(N)=CN(N)=CSIN(CPSI(N+1,I))
C          IF(FP.EQ.2.)CNN(N)=CN(N)/CSIN(CPSI(N+1,I))
75  CONTINUE
C
C      IF(FP.EQ.1.)RRINDO=RRINDO*SIN(REAL(CPSI(1,I)))
C      IF(FP.EQ.2.)RRINDO=RRINDO/SIN(REAL(CPSI(1,I)))
C      CN(NL1)=(1.,0.)
C      CNN(NL1)=RRINDO
C
C      SET UP DENOMINATOR AND INCIDENT MEDIUM FIELD AMPLITUDES
C
C          CEZERO = CHMAT(1,1,I)-CHMAT(2,1,I)
C          CHZERO = CNN(NL1)-(CHMAT(1,1,I)-CHMAT(2,1,I))
C          RED=REAL(CEZERO+CHZERO/RRINDO)=REAL(CEZERO-CHZERO/RRINDO)
C          AIMD=AIMAG(CEZERO+CHZERO/RRINDO)=AIMAG(CEZERO-CHZERO/RRINDO)
C          DENOM=0.25*RRINDO-(RED+AIMD)
C
C      INITIALIZE MATRIX PRODUCT
C
C          CHMATO(1,1)=1.0
C          CHMATO(1,2)=0.0
C          CHMATO(2,1)=0.0
C          CHMATO(2,2)=1.0
C
C      CALCULATE INITIAL POYNTING VECTOR AMPLITUDE
C
C          CONJH=CONJG(CHZERO)
C          POYNTJM=REAL(CEZERO-CONJH)
C
C      CALCULATE INVERSE MATRIX FOR LAYER J
C
C      IFLAG=0
C      DO 100 J=1,Nlayer
C
C      CHECK IF LAYER BEFORE HAD NO ENERGY DEPOSITED
C      SAVE CALCULATION
C
C      IF(IFLAG.EQ.1)THEN
C          DE(J,I)=0.
C          GOTO 100
C      END IF
C      CAPPHI=2.*PI-(E(I)/EVCM)*CP(J,I)-Z(J)
C      CHMAT1(1,1)=CCOS(CAPPHI)
C
C      CHMAT1(1,2)=-CI-CSIN(CAPPHI)/CNN(J)

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```

C      CHMAT1(2,1)=-CI-CSIN(CAPPHI)-CNN(J)
C      CHMAT1(2,2)=CCOS(CAPPHI)
C
C
C      MULTIPLY PRODUCT BY NEW INVERSE
C      CALL MMULTI(CHMAT0,CHMAT1)
C
C      CALCULATE CORRESPONDING ELECTRIC AND MAGNETIC FIELD AMPLITUDES
C      AND POYNTING VECTOR AMPLITUDE
C
C      CESUBJ=CHMAT0(1,1)=CEZERO + CHMAT0(1,2)=CHZERO
C      CHSUBJ=CHMAT0(2,1)=CEZERO + CHMAT0(2,2)=CHZERO
C      CONJHJ=CONJG(CHSUBJ)
C      CPOYNTJ=CESUBJ*CONJHJ
C      POYNTJ=REAL(CPOYNTJ)
C
C      TAKE THE DIFFERENCE IN POYNTING VECTOR AMPLITUDES TO GIVE YOU
C      THE ABSORPTANCE
C
C      DE(J,I)=(POYNTJM-POYNTJ)/DENOM
C      IF(DE(J,I).LE.O.OR.POYNTJ.LT.O.)THEN
C        IFLAG=1
C        DE(J,I)=G.
C      ENDIF
C
C      REINITIALIZE J-1 POYNTING VECTOR AMPLITUDE
C      POYNTJM=POYNTJ
C
C      CALCULATE NORMAL ABSORPTION
C      GET CORRESPONDING MASS ABSORPTION COEFFICIENT
C
C      IEL=ISTRUC(1,1,J)
C      CALL F1F2T(IEL,OUTFIL,EMF)
C      RMUFACT=EMF/E(I)
C      RMU=EINTRP(E(I),OUTFIL(1,2))-RMUFACT
C
C      CALCULATE FRACTION TRANSMITTED AND FRACTION ABSORBED
C
C      TRANS=EXP(-Z(J)-DENS(J)-RMU/SIN(REAL(CPSI(1,1))))
C      ABSORP=1.-TRANS
C      DEA(J,I)=ABSORP*THRUU(I)
C      THRUU(I)=TRANS*THRUU(I)
C      DE(J,I)=DEA(J,I)
C      100 CONTINUE
C      200 CONTINUE
C      DO 300 II=1,1
C        WRITE(12,1929)
C      1929 FORMAT(' ABSORBER DE')
C      WRITE(12,1930)(DEA(J,II),J=1,NLAYER)
C      300 CONTINUE
C      1930 FORMAT(1P6E12.4)
C      RETURN
C      ENC
C      SUBROUTINE MMULTI(CHMAT,CHMAT1)
C      PARAMETER (LAY=60)
C      COMPLEX CHMAT(2,2),CHMAT1(2,2),CSUM(2,2)
C
C      COMPLEX MATRIX MULTIPLICATION OF 2 MATRICES
C
C      DO 100 I=1,2
C      DO 100 J=1,2
C      CSUM(I,J)=(O..O.)
C      DO 50 K=1,2
C      CSUM(I,J)=CSUM(I,J)+CHMAT1(I,K)*CHMAT(K,J)
C      100 CONTINUE
C      DO 200 I=1,2
C      DO 200 J=1,2
C      200 CHMAT(I,J)=CSUM(I,J)
C      RETURN
C      END
C      SUBROUTINE SPECTRM(TIME,NPOINTS,E)

```



```

C      OBTAINS THE SPECTRUM THRU(I) AT TIME TIME
C
C      PARAMETER(LAY=60)
C
C      DIMENSION E(100)
COMMON /TIME/ NTIME, TIMES(60), ASDRCE, DLSM, DDET, ITSAVE
COMMON /RTD/R(100), THRU(100), DEINT(LAY), DESUM(LAY), TEMP(LAY), DT
COMMON /INTP/OUTFIL1(100),OUTFIL2(100)
C
C      I1 --- POINTER FOR EARLIER TIME
C      I2 --- POINTER FOR LATER TIME
C
C      DETERMINE WHICH TIMES BRACKET THE PARTICULAR TIME
C
C      CALL TINTRP(TIME, I1, I2)
C
C      READ APPROPRIATE SPECTRUM
C
C      CALL SPECT(I1,OUTFIL1,NPOINTS)
C      CALL SPECT(I2,OUTFIL2,NPOINTS)
C
C      INTERPOLATE SPECTRUM AT TIME TIME
C
C      CALL HERM1(TIME, TIMES(I1), TIMES(I2), NPOINTS)
DO 20 J=1, NPOINTS
    THRU(J) = ((TIME - TIMES(I1)) / (TIMES(I2) - TIMES(I1))) *
    * (OUTFIL2(J) - OUTFIL1(J)) + OUTFIL1(J)
20 CONTINUE
C
C      RETURN
END
C--
C-- SUBROUTINE HERM1(TIME, T1, T2, NPOINTS)
C--
C-- THIS SUBROUTINE CALCULATES THE SPECTRUM THRU(I) AT THE
C-- INTERPOLATED TIME BY HERMITE CUBIC INTERPOLATION
C--
C-- PARAMETER(LAY=60)
C-- COMMON /RTD/R(100), THRU(100), DEINT(LAY), DESUM(LAY), TEMP(LAY), DT
C-- COMMON /INTP/OUTFIL1(100),OUTFIL2(100)
C--
C-- DX=TIME-T1
C-- DT=T2-T1
C-- DTS=0.5*DT
C-- DDT=1./DT
C-- DO 100 I=1, NPOINTS
C--     YVAR1=0.
C--     DYDX1=OUTFIL1(I)
C--     DYDX2=OUTFIL2(I)
C--     YVAR2=YVAR1+DTS*(DYDX1+DYDX2)
C--     DVF1=(YVAR2-YVAR1)-DDT
C--     DVF3=DYDX1-DYDX2-2.*DVF1
C--     C3=(DVF1-DYDX1-DVF3)*DDT
C--     C4=DVF3-DDT**2
C--     THRU(I)=DYDX1+DX*(2.*C3+3.*DX+C4)
C-- 100 CONTINUE
C-- RETURN
C-- END
C-- SUBROUTINE SPECT(IT,OUTFIL,NPTS) .
C
C      THIS SUBROUTINE READS THE SPECTRUM AT LOCATION IT
C      AND PUTS IT IN FILE OUTFIL
C
C      DIMENSION OUTFIL(100)
IADDR=(IT)-NPTS+1
CALL RDISK(2,OUTFIL,NPTS,IADDR)
IF(UNIT(2)) 11,100,110
11 RETURN
100 WRITE(6,1000)
1000 FORMAT(' EOF ON FILE SPECTRUM')
RETURN
110 WRITE(6,1001)
1001 FORMAT(' I/O ERROR ON FILE SPECTRUM')
RETURN
END
SUBROUTINE RDENGY(E,NE)
C

```

C THIS SUBROUTINE READS IN THE NUMBER OF AND ENERGY VALUES
C FOR THE SPECTRUM ARRAYS

```

      DIMENSION E(1)
      IADDR=0
      CALL RDISK(2,NE,1,IADDR)
      IF(UNIT(2)) 11,100,110
11    IADDR=IADDR+1
      CALL RDISK(2,E,NE,IADDR)
      IF(UNIT(2)) 12,100,110
12    RETURN
100  WRITE(6,1000)
1000 FORMAT(' EDF ON FILE SPECTRUM')
      RETURN
110  WRITE(6,1001)
1001 FORMAT(' I/O ERRDR ON FILE SPECTRUM')
      RETURN
      END
      SUBROUTINE RTIME

```

C
C THIS SUBROUTINE READS THE TIMES THAT SPECTRUM ARE AVAILABLE
C

```

      COMMON /TIME/NTIME,TIMES(60),ASORCE,DLSM,ODET,ITSAVE
      READ(97,1)NTIME
1    FORMAT(I2)
      READ(97,2)(TIMES(J),J=1,NTIME)
2    FORMAT(F4.1)
      RETURN
      END
      SUBROUTINE TINTRP(TIME,I1,I2)

```

C
C THIS SUBROUTINE DETERMINES THE TWO TIMES THAT BRACKET
C THE TIME FOR INTERPOLATION LATER
C

```

      COMMON /TIME/NTIME,TIMES(60),ASORCE,DLSM,ODET,ITSAVE
C
      DO 100 I=ITSAVE,NTIME
        IF(TIME.LT.TIMES(I))GOTO 150
100    CONTINUE
        I2=NTIME
        I1=NTIME-1
        ITSAVE=I2
        GOTO 170
150    IF(I.EQ.1)THEN
          WRITE(1,10)
10    FORMAT(' TIME NOT WITHIN DATA BOUNDS ABORTING PROGRAM')
          STOP
        ELSE
          I1=I-1
          I2=I
        ENDIF
        ITSAVE=I2
170    RETURN
      END
      SUBROUTINE TRANSM(R1,E,N,R2)

```

C
C THIS SUBROUTINE DETERMINES THE FILTER TRANSMISSION AT ENERGY E AND
C MULTIPLIES THE TRANSMISSION BY THE SPECTRUM
C

```

      DIMENSION OUTFIL(400,2),R1(N),R2(N),E(N)
      COMMON /ENLOG/ENERGY(400),MAX
      THICK=123.56E-6

```

C
C DETERMINE MU
C

```

      IEL=13
      CALL F1F2(IEL,OUTFIL,ATWT,RMU,EMF,NAME)

```

C
C DO 10 I=1,N
C RMUFACT=EMF/E(I)
C RMU=EINTRP(E(I),OUTFIL(1,2))=RMUFACT

C
C CALCULATE THE TRANSMISSION
C

```

      TRANS=EXP(-RMU*THICK)
      R1(I)=R1(I)*TRANS
      R2(I)=R2(I)*TRANS
10    CONTINUE
      RETURN
      END

```

```

      SUBROUTINE SWITCH(CUT,RIN)
      C
      C THIS SUBROUTINE SWITCHES ARRAY VALUES OF RIN INTO ARRAY OUT
      C
      DIMENSION RIN(400,2),OUT(400,2)
      DO 100 I=1,400
      DO 50 J=1,2
      OUT(I,J)=RIN(I,J)
      50 CONTINUE
      100 CONTINUE
      RETURN
      END
      SUBROUTINE F1F2T(IEL,OUTFIL,EMF)
      C
      C C THIS SUBROUTINE GETS THE APPROPRIATE F1 AND F2 AND EMF
      C C C
      COMMON /ENLOG/ ENERGY(400),MAX
      COMMON /F1F2/IH,IL,F1F2H(400,2),F1F2L(400,2),
      F1F2S(400,2),IS,ATWTH,ATWTL,ATWTS,EMFH,EMFL,EMFS
      COMMON /EN/MAXH,MAXL,MAXS,EL(400,2),ES(400),EH(400)
      DIMENSION OUTFIL(400,2)
      C
      IF(IEL.EQ.IH)THEN
      CALL SWITCH(OUTFIL,F1F2H)
      CALL SWITCH(ENERGY,MAX,EH,MAXH)
      EMF=EMFH
      ENDIF
      IF(IEL.EQ.IL)THEN
      CALL SWITCH(OUTFIL,F1F2L)
      CALL SWITCH(ENERGY,MAX,EL,MAXL)
      EMF=EMFL
      ENDIF
      IF(IEL.EQ.IS)THEN
      CALL SWITCH(OUTFIL,F1F2S)
      CALL SWITCH(ENERGY,MAX,ES,MAXS)
      EMF=EMFS
      ENDIF
      RETURN
      END

```

```

=RCFT I=%ME
=LDR B=(BMSPEXP,BCSPEXP).X=XSPEXP1.LIB=(CFTLIB,DISCFT)

C      -----BEGINNING OF SUBROUTINE THAT READS A NEW
C      -----CPYICAL ELEMENT STRUCTURE.
SUBROUTINE OPT1(NLAYER,NPERIOD,NE,ANG)
PARAMETER (LAY=60)
IMPLICIT COMPLEX (C)
COMMON ASCAT(LAY,100),BSCAT(LAY,100),ISTRUC(4,2,LAY)
COMMON DENS(LAY),CPSI(LAY,100),Z(LAY),E(100),CP(LAY,100)
COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RINDO,CI,CPSIO

C
C      ASSIGN 9000 TO INTADR
CALL IENABL(INTADR)

I1=1
I2=0
CALL OPT1A(I1,I2,NPERIOD,-760)
NLAYER=I2
RETURN

760 CALL DISABL
RETURN

C      INTERRUPT ROUTINE .. HANDLES CTRL-E I
9000 CALL INTERR
RETURN

END

SUBROUTINE OPT1A(I1,I2,NPERIOD,=)

C
C      THIS SUBROUTINE SETS UP THE INITIAL MULTILAYER STRUCTURE
C      CODE.
C
C      VARIABLES
C
C      DENS(I) --- THE DENSITY OF LAYER I
C      DESUM(I) --- ENERGY CONTENT OF LAYER I
C      ISTRUCT(N,1,I)---THE ATOMIC NUMBER OF THE N'TH ELEMENT OF THE I'TH LAYER
C      ISTRUCT(N,2,I)---THE NUMBER OF ATOMS OF THE N'TH ELEMENT OF THE I'TH LAYER
C      I2 ---RETURNS NLAYER TO THE CALLING ROUTINE
C      NLAYER --- THE NUMBER OF LAYERS INCLUDING THE SUBSTRATE
C      NPERIOD --- THE NUMBER OF PERIODS ,ASSUMED TO BE 1 FOR THIS CASE
C      TEMP(I) - TEMPERATURE OF LAYER I
C      Z(I)=== THE PHYSICAL THICKNESS OF THE I'TH LAYE
C
PARAMETER (LAY=60)

IMPLICIT COMPLEX (C)
COMMON ASCAT(LAY,100),BSCAT(LAY,100),ISTRUC(4,2,LAY)
COMMON DENS(LAY),CPSI(LAY,100),Z(LAY),E(100),CP(LAY,100)
COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RINDO,CI,CPSIO
= F1F2S(400,2),IS,ATWTH,ATWTL,ATWTS,EMFH,EMFL,EMFS
COMMON /EN/MAXH,MAXL,MAXS,EL(400),ES(400),EH(400)
COMMON /ENLOG/ ENERGY(400),MAX
COMMON /RTD/ R(100),THRU(100),DEINT(LAY),DESUM(LAY),TEMP(LAY),DT

C
C
NLAYER=55
I2=NLAYER
NPERIOD=1
NL=NLAYER-1
DO 1000 I=1,NL,2
ISTRUC(1,1,I+1)=74
ISTRUC(1,2,I+1)=1
ISTRUC(2,1,I+1)=0
ISTRUC(2,2,I+1)=0
DENS(I+1)=19.3
Z(I+1)=24.980E-9
ISTRUC(1,1,I)=6
ISTRUC(1,2,I)=1
ISTRUC(2,1,I)=0
ISTRUC(2,2,I)=0
DENS(I)=2.00
Z(I)=42.52E-9
1000 CONTINUE

```

[illegible]

```

100 CONTINUE
C
C   REINITIALIZE INCIDENT ANGLES
C
      DO 105 I=1,NA
105  CPSI(1,I)=RANG

C
C   CALCULATE REFLECTIVITY AND ABSORPTION FOR 'P' CASE
C
      FP=2.
      CALL INIMAT (CHMAT)
      CALL PERIODO(NPERIOD,CHMAT,NE,NLAYER)
      CALL COMBINE(CHMAT,NE,NLAYER)
      CALL DELTAE(CHMAT,NE,DE2,NLAYER)

C
C   COMBINE 'S' AND 'P' RESULTS TO GET UNPOLARIZED CASE
C
      DO 110 I=1,NN
        R(I)=.5*(R(I)+RTMP(I))
        DO 102 J=1,NLAYER
          DE(J,I)=0.5*(DE(J,I)+DE2(J,I))
102      CONTINUE
110    CONTINUE

      RETURN

C   INTERRUPT ROUTINE .. HANDLES CTRL-E I
9000 CALL INTERR
      RETURN
      END
      SUBROUTINE OPT4(NLAYER,NPERIOD,NE,RANG,RINT,RTINT)

C
C   THIS SUBROUTINE IS THE MAIN DRIVER TO CALCULATE REFLECTIVITY, AND ABSORPTION
C   IN EACH LAYER AS WELL AS THE REFLECTED AND FILTERED THRUPUTS
C
      PARAMETER (LAY=60)
      IMPLICIT COMPLEX (C)
      DIMENSION CHMAT(2,2,100),DE(LAY,100),HSTATE(LAY),DETEMP(100)
      COMMON ASCAT(LAY,100),BSCAT(LAY,100),ISTRUC(4,2,LAY)
      COMMON DENS(LAY),CPSI(LAY,100),Z(LAY),E(100),CP(LAY,100)
      COMMON /CONS/ RAD,PI,RO,AMU,ANGEV,EVCM,RINDO,C1,CPSIC
      COMMON /RTD/ R(100),THRU(100),DEINT(LAY),DESUM(LAY),TEMP(LAY),DT
      COMMON /POLAR/ FP
      COMMON /TIME/NTIME,TIMES(60),ASGRCE,DLSM,DDET,ITSAVE

C ANGR---- INCIDENT ANGLE IN RADIANS
C ASORCE -- SOURCE AREA
C CANG ---- INCIDENT ANGLE
C CPSI(N+1,I) --- ANGLE IN LAYER N AT POINT I
C DE(KK,JJ) --- ABSORPTION IN LAYER KK FOR POINT JJ
C DEINT(KK) --- ABSORPTION INTEGRATED OVER ALL ENERGY FOR LAYER KK
C DT -- TIME STEP
C DESUM(KK) --- ABSORPTION INTEGRATED OVER TIME AND ENERGY
C DDET -- DISTANCE FROM SOURCE TO DETECTOR
C DLSM -- DISTANCE FROM LSM TO SOURCE
C E(I) --- ENERGY AT POINT I
C EMIN --- MINIMUM ENERGY IN EV
C EMAX --- MAXIMUM ENERGY IN EV
C FP --- POLARIZATION FLAG
C --- FP =1. THEN "S" POLARIZATION
C --- FP =2. THEN "P" POLARIZATION
C NE --- NUMBER OF POINTS OF ENERGY
C NLAYER --- NUMBER OF LAYERS INCLUDING THE SUBSTRATE
C NPERIOD --- NUMBER OF PERIODS IN HEATING CASE NPERIOD =1
C NPOL --- POLARIZATION STATE
C RINT --- INTEGRATED REFLECTIVITY=SPECTRUM OVER ALL ENERGY
C RTINT --- INTEGRATED REFLECTIVITY-SPECTRUM-TRANSM OF FILTER OVER ALL ENERGY
C TEMP(KK) --- TEMPERATURE OF LAYER KK
C THRU(I) --- SPECTRUM AT DIFFERENT POINTS IN THE PATH AT EACH ENERGY I
C
C
C   INITIALIZE VARIABLES
C
      WRITE(1,1954)DT

```

```

1954 FORMAT(F10.4)
      ASORCE=1.
      DLSM=.50.
      DDET=.159.30
      ANGR=.1093
      EMIN=E(1)
      EMAX=E(NE)
      NPOL='U'
      NMAX=99
      ASSIGN 9000 TO INTADR
      CALL IENABL(INTADR)
C
      ITHRU=0
      CANG=ANGR
      CPSI(1,1)=CANG
      RANG=CANG
      NANG=0
C
C   INITIALIZE ANGLE FOR ALL I
C
      DO 1400 I=1,NMAX
1400  CPSI(1,I)=CPSI(1,1)
C
C   SET POLARIZATION FLAG
C
      IF (NPOL.EQ.'S') FP=1.
      IF (NPOL.EQ.'P') FP=2.
      IF (NPOL.EQ.'U') THEN
C
C   CALCULATE R AND DELTA E ABSORBED
C
          CALL UNPOLAR(NLAYER,NPERIOD,NMAX,RANG,DE)
      ELSE
          CALL INIMAT (CHMAT)
          CALL PERIODO(NPERIOD,CHMAT,NMAX,NLAYER)
          CALL COMBINE(CHMAT,NMAX,NLAYER)
          CALL DELTAE(CHMAT,NMAX,DE,NLAYER)
      ENDIF
C
C   IF (NANG.EQ.0) CPSI(1,1)=CANG
C
C
C   WRITE OUT R,E UNIT RESPONSE
C
      WRITE(8,1930)(R(JJ),JJ=1,NMAX)
      WRITE(8,1955)
C
C   CONVERT INCIDENT SPECTRUM THRU FROM UNITS OF MW/CM==2-SR/KEV
C   TO MW/CM==2/EV
C
      BOLXRD = ANISOTROPY FACTOR
C
      BOLXRD=4.0
      DLSM2=DLSM==2
      DDET2=DDET==2
      DO 1830 KL=1,NMAX
          THRU(KL)=THRU(KL)=(ASORCE/DLSM2)/(1000.)=BOLXRD
1830  CONTINUE
          CALL AVINT(E,THRU,NMAX,E(1),E(NMAX),THRUINT,IERR)
          WRITE(8,1937)THRUINT
1937  FORMAT(' INTEGRATED INCIDENT FLUX',1PE12.4)
1930  FORMAT(6E12.4)
C
C   MULTIPLY UNIT ABSORPTANCE BY INCIDENT SPECTRUM
C   AND TIME TO GET ABSORPTION (J/CM==2) (NS X MW = E-3)
C   AND FOR EACH ENERGY MULTIPLY REFLECTIVITY BY SPECTRUM
      DO 2275 JJ=1,NMAX
          DO 2250 KK=1,NLAYER
              DE(KK,JJ)=THRU(JJ)=DE(KK,JJ)*DT=1E-3
              DE(KK,JJ)=THRU(JJ)=DE(KK,JJ)
C
2250  CONTINUE
2275  CONTINUE
          WRITE(12,1930)(DE(KK,1),KK=1,NLAYER)
          WRITE(12,1955)
C

```

```

      DO 2300 JJ=1,NMAX
C
C      FOR EACH ENERGY MULTIPLY SPECTRUM BY REFLECTIVITY
C
        THRU(JJ)=R(JJ)*THRU(JJ)
2300 CONTINUE
C
C      INTEGRATE TO GET INTEGRATED REFLECTIVITY=SPECTRUM
C
C      WRITE(8,1930)(THRU(JJ),JJ=1,NMAX)
C
C      CALL AVINT(E,THRU,NMAX,E(1),E(NMAX),RINT,IERR)
C
C      FOR EACH LAYER KK INTEGRATE ABSORPTION OVER ALL ENERGY
C
        DEPLUS=0.
        DO 2400 KK=1,NLAYER
          DO 2350 JJ=1,NMAX
            DETEMP(JJ)=DE(KK,JJ)
2350 CONTINUE
          CALL AVINT(E,DETEMP,NMAX,E(1),E(NMAX),DEINT(KK),IERR)
          DEPLUS=DEPLUS+DEINT(KK)
2400 CONTINUE
          WRITE(13,1930)(DEINT(KK),KK=1,NLAYER)
          WRITE(13,1955)
          WRITE(13,1934)DEPLUS
1934 FORMAT(' SUMMED ENERGY',1PE12.4)
C
C      LOOK UP TEMPERATURE ALONG ENTHALPY PLOT ADD INTEGRATED ENERGY
C      AND CALCULATE EXPANSION
C
C      TEMPERATURE TEMP IS IN DEGREES KELVIN
C      HRATE IS IN W/G
C      ENTHALPY H IS IN J/G
C      DENS IS IN G/CM**2
C
        FAC=1.
        DO 3000 KK=1,NLAYER
          DESUM(KK)=DESUM(KK)+DEINT(KK)/(DENS(KK)*Z(KK))
          H=DESUM(KK)
          TEMP2=TEMPH(KK,H)
          DTEMP=TEMP2-TEMP(KK)
          IF(KK.LT.3)FAC=3.
          ALPHA=EXPAN(KK,TEMP(KK))=FAC
          TEMP(KK)=TEMP2
          DZ=ALPHA*DTEMP=Z(KK)
          DENS(KK)=DENS(KK)+Z(KK)/(Z(KK)+DZ)
          Z(KK)=Z(KK)+DZ
          HRATE(KK)=H/(DT=1E-9)
3000 CONTINUE
          WRITE(7,1930)(TEMP(KK),KK=1,NLAYER)
          WRITE(7,1955)
          WRITE(9,1930)(Z(KK),KK=1,NLAYER)
          WRITE(10,1930)(DESUM(KK),KK=1,NLAYER)
          WRITE(10,1955)
          WRITE(9,1955)
          WRITE(11,1930)(HRATE(KK),KK=1,NLAYER)
          WRITE(11,1955)
1955 FORMAT(' ')
C
C      CALCULATE TRANSMITTED SPECTRUM THROUGH THE FILTER
C      FOR BOTH THE REFLECTED AND THE UNIT REFLECTED SPECTRUM
C
        CALL TRANSM(THRU,E,NMAX,R)
C
C      WRITE(1,1930)(R(LL),LL=1,NMAX)
C
C      WRITE(1,1955)
C
C      MULTIPLY REFLECTED = TRANSMITTED SPECTRUM
C      BY FLUOR CONVERSION EFFICIENCY
C
        DO 2500 IC=1,NMAX
          IF(E(IC).LE.283.84)THEN
            THRU(IC)=THRU(IC)*1.852E-4=(E(IC)==0.46)
          ELSE IF(E(IC).GT.283.84.AND.E(IC).LT.311.7) THEN
            THRU(IC)=THRU(IC)*8.015E-5=(E(IC)==0.46)
          ELSE

```



```

C TAKE INTO ACCOUNT THE DOPANT GRADIENT
C
      THRU(IC)=THRU(IC)-FLUGR(E(IC))*8.015E-5
      ENDIF
C
C TAKE INTO ACCOUNT DISTANCE DETECTOR IS FROM SOURCE
C
      THRU(IC)=THRU(IC)*(OLSM2/ODET2)
2500 CONTINUE
C
C
C INTEGRATE REFLECTION-TRANSM-SPECTRUM-FLUOR RESPONSE - OVER ALL ENERGY
C
      CALL AVINT(E,THRU,NMAX,E(1),E(NMAX),RTINT,IERR)
C
      WRITE(1,1932)RTINT,RTINT
1932 FORMAT(' R=S INTEGRATED',E15.5,' R=S-T INTEGRATED',E15.5)
C
      WRITE(1,1930)(DEINT(KK),KK=1,NLAYER)
C
      RETURN
1111 FORMAT(2X,'ILLEGAL INPUT. RETYPE.')
```

888 CALL DISABL
RETURN

9000 CALL INTERR
RETURN

END
SUBROUTINE INTERR

C
C
C INTERRUPT SUBROUTINE

PARAMETER (LAY=60)
CALL QCLRSTK
CALL IREL(1)
CALL MSGFT
RETURN
END
FUNCTION ETRP(E,SP,EN,NN)
DIMENSION SP(100),EN(100)

C
C THIS FUNCTION INTERPOLATES THE ENERGY
C

DO 100 I=1,NN
IF(E.LT.EN(I)) GOTO 150
100 CONTINUE
I=NN
120 ETRP=SP(I)
RETURN

150 IF (I.EQ.1) GOTO 120
EN2=ALOG(EN(I))
EN1=ALOG(EN(I-1))
ETRP=(ALOG(E)-EN1)/(EN2-EN1)*(SP(I)-SP(I-1))+SP(I-1)
RETURN
END

SUBROUTINE AVGDENS(TDENS,ISSTRUC)

C
C THIS SUBROUTINE AVERAGES THE DENSITY
C

PARAMETER (LAY=60)
DIMENSION ISSTRUC(4,2)
NTOT=0
DO 100 I=1,4
IF(ISSTRUC(I,1).EQ.0) GOTO 200
NTOT=NTOT+ISSTRUC(I,2)
100 CONTINUE
200 TDENS=TDENS/NTOT
RETURN
END
SUBROUTINE SWITCHE(E1,MAX1,E2,MAX2)

C
C
C SWITCHES THE VALUES IN E2 AND MAX2 TO THAT OF E1 AND MAX1

DIMENSION E1(1),E2(1)
MAX1=MAX2
DO 30 J=1,MAX2

```

      E1(J)=E2(J)
30  CONTINUE
      RETURN
      END
      FUNCTION TEMPH(N,H)

C
C  THIS FUNCTION GETS THE APPROPRIATE TEMPERATURE FROM THE APPROPRIATE
C  ENTHALPY CURVE
C
      PARAMETER (LAY=60)
      COMMON ASCAT(LAY,100),BSCAT(LAY,100),ISTRUC(4,2,LAY)
      IF(ISTRUC(1,1,N).EQ.6)THEN
        TEMPH=CARBON(H)
      ELSE IF (ISTRUC(1,1,N).EQ.74)THEN
        TEMPH=TUNGSTEN(H)
      ELSE IF (ISTRUC(1,1,N).EQ.14)THEN
        TEMPH=SILICON(H)
      END IF
      RETURN
      END
      FUNCTION EXPAN(N,TEMP)

C
C  THIS FUNCTION DETERMINES THE APPROPRIATE LINEAR EXPANSION
C  COEFFICIENT
C
      PARAMETER (LAY=60)
      COMMON ASCAT(LAY,100),BSCAT(LAY,100),ISTRUC(4,2,LAY)

C
C  DETERMINE THE LAYER TYPE
C
      IF(ISTRUC(1,1,N).EQ.6)THEN
        EXPAN=ALPHAC(TEMP)
      ELSE IF(ISTRUC(1,1,N).EQ.74)THEN
        EXPAN=ALPHAH(TEMP)
      ELSE IF(ISTRUC(1,1,N).EQ.14)THEN
        EXPAN=ALPHAS(TEMP)
      ENDIF
      RETURN
      END
      FUNCTION FLUOR(E)

C
C  THIS FUNCTION LOOKS UP THE TEMPERATURE ALONG THE
C  NE111 FLUORESCER CURVE
C
      E --- ENERGY
      FLUOR --- CONVERSION EFFICIENCY (W EMITTED/WABSORBED)

      DATA CO/1.218E1/,C1/8.875E-3/,C2/5.524E-5/,C3/-5.978E-8/
      DATA CO2/-6.201E1/,C12/3.420E-1/,C22/-4.716E-4/,C32/2.683E-7/
      DATA C42/-5.568E-11/
      DATA CO3/2.986E1/,C13/-1.470E-2/,C23/2.903E-6/,C33/-2.617E-10/
      DATA C43/8.887E-15/
      E2=E-E
      E3=E2-E
      IF(E.LE.676.8)THEN
        FLUOR=CO+E-C1+E2-C2+E3-C3
      ELSE IF(E.GT.676.8.AND.E.LE.1486.7)THEN
        FLUOR=CO2+E-C12+E2-C22+E3-C32+E3-E-C42
      ELSE IF(E.GT.1486.7) THEN
        FLUOR=CO3+C13+E+C23-E2+C33-E3+C43-E2-E2
      END IF
      RETURN
      END
      FUNCTION TUNGSTEN(H)

C
C  THIS FUNCTION LOOKS UP THE TEMPERATURE ALONG THE
C  TUNGSTEN ENTHALPY CURVE
C
      H --- ENTHALPY
      TUNGSTEN --- TEMPERATURE SEARCHING FOR

      DATA CO/2.982E2/,C1/7.331E0/,C2/-3.070E-3/,C3/1.302E-6/
      DATA CO2/-4.080E1/,C12/4.599E0/,C22/6.020E-4/,C32/-2.052E-7/
      H2=H-H
      H3=H2-H
      IF(H.LE.561.75)THEN
        TUNGSTEN=CO+H-C1+H2-C2+H3-C3
      ELSE IF(H.GT.561.75.AND.H.LE.753.91) THEN
        TUNGSTEN=3680.
      ELSE IF(H.GT.753.91.AND.H.LE.1201.8)THEN

```

```

      TUNGSTEN=CO2+C12+H+C22+H2+C32+H3
ELSE
      TUNGSTEN = 0.0
END IF
RETURN
END
FUNCTION CARBON(H)
C
C THIS FUNCTION LOOKS UP THE TEMPERATURE ALONG THE
C CARBON ENTHALPY CURVE
C
H --- ENTHALPY
CARBON --- TEMPERATURE SEARCHING FOR
C
      DATA CO/2.982E2/,C1/1.265E0/,C2/-1.579E-3/,C3/1.964E-6/
      DATA C4/-1.243E-9/,C5/3.051E-13/
      DATA CO2/4.262E2/,C12/6.312E-1/,C22/-5.682E-5/,C32/1.128E-8/
      DATA C42/-1.159E-12/,C52/4.665E-17/
      H2=H-H
      H3=H2-H
      IF(H.LE.1164.8)THEN
        CARBON=CO+H+C1+H2+C2+H3+C3+H3+H+C4+H3+H2+C5
      ELSE IF(H.GT.1164.8.AND.H.LE.7583.9)THEN
        CARBON=CO2+H+C12+H2+C22+H3+C32+H3+H+C42+H3+H2+C52
      ELSE IF(H.GT.7583.9) THEN
        CARBON=0.0
      END IF
      RETURN
      END
      FUNCTION SILICON(H)
C
C THIS FUNCTION LOOKS UP THE TEMPERATURE ALONG THE
C SILICON ENTHALPY CURVE
C
H --- ENTHALPY
SILICON --- TEMPERATURE SEARCHING FOR
C
      DATA CO/2.982E2/,C1/1.321E0/,C2/-4.507E-4/,C3/3.284E-7/
      DATA C4/1.665E-11/,C5/-1.768E-13/,C6/7.063E-17/
      DATA CO2/-1.634E2/,C12/1.066E0/,C22/4.769E-6/
      H2=H-H
      H3=H2-H
      IF(H.LE.1275.)THEN
        SILICON=CO+H+C1+H2+C2+H3+C3+C4+H3+H+C5+H3+H2+C6+H3+H3
      ELSE IF(H.GT.1275..AND.H.LE.3072.6) THEN
        SILICON=1685.
      ELSE IF(H.GT.3072.6.AND.H.LE.4803.4)THEN
        SILICON=CO2+C12+H+C22+H2
      ELSE
        SILICON = 0.0
      END IF
      RETURN
      END
      FUNCTION ALPHAW(T)
C
C THIS FUNCTION DETERMINES THE EXPANSION COEFFICIENT
C OF TUNGSTEN FOR THE GIVEN TEMPERATURE T
C
      DATA CO/5.006E-6/,C1/-3.708E-9/,C2/8.256E-12/,C3/-5.653E-15/
      DATA C4/1.267E-18/
      DATA CO2/4.632E-6/,C12/1.907E-9/,C22/-2.258E-12/,C32/1.106E-15/
      DATA C42/-1.324E-19/
C
      T2=T-T
      T3=T2-T
      IF(T.LE.1200.0)THEN
        ALPHAW=CO+T+C1+T2+C2+T3+C3+T3+T+C4
      ELSE IF(T.GT.1200.0) THEN
        ALPHAW=CO2+C12+T+C22+T2+C32+T3+C42+T+T3
      END IF
      RETURN
      END
      FUNCTION ALPHASI(T)
C
C THIS FUNCTION DETERMINES THE EXPANSION COEFFICIENT
C OF SILICON FOR THE GIVEN TEMPERATURE T
C
      DATA CO/-5.740E-6/,C1/6.417E-8/,C2/-1.894E-10/,C3/2.906E-13/
      DATA C4/-2.234E-16/,C5/6.848E-20/
      DATA CO2/3.400E-6/,C12/1.000E-9/

```

```

DATA C03/4.600E-5/
DATA C04/3.900E-6/,C14/5.000E-10/
C
T2=T-T
T3=T2-T
IF (T.LE.900.) THEN
    ALPHAS1=C0+T-C1+T2-C2+T3-C3+T3-T-C4+C5-T3-T2
ELSE IF (T.GT.900..AND.T.LE.1200.0) THEN
    ALPHAS1=C02+C12-T
ELSE IF (T.GT.1200.0.AND.T.LE.1400.0) THEN
    ALPHAS1=C03
ELSE IF (T.GT.1400.0) THEN
    ALPHAS1=C04+C14-T
END IF
RETURN
END
FUNCTION ALPHAC(T)
C
C THIS FUNCTION DETERMINES THE EXPANSION COEFFICIENT
C OF CARBON FOR THE GIVEN TEMPERATURE T
C
DATA C0/2.635E-6/,C1/2.188E-9/,C2/-2.757E-12/,C3/2.544E-15/
DATA C4/-9.172E-19/,C5/1.239E-22/
C
T2=T-T
T3=T2-T
ALPHAC=C0+T-C1+T2-C2+T3-C3-T3-T-C4+C5-T3-T2
RETURN
END

```